Membrane & Desalination Research - Singapore Membrane Technology Centre

Tony FANE and Ziggy CHONG

Singapore Membrane Technology Centre

NANYANG TECHNOLOGICAL UNIVERSITY

SMTC

Member of
the NEWRI Ecosystem

NANYANG TECHNOLOGICAL UNIVERSITY

Nanyang Environment & Water Research Institute

NEWRI ECOSYSTEM

Your Global Research & Technology Partner

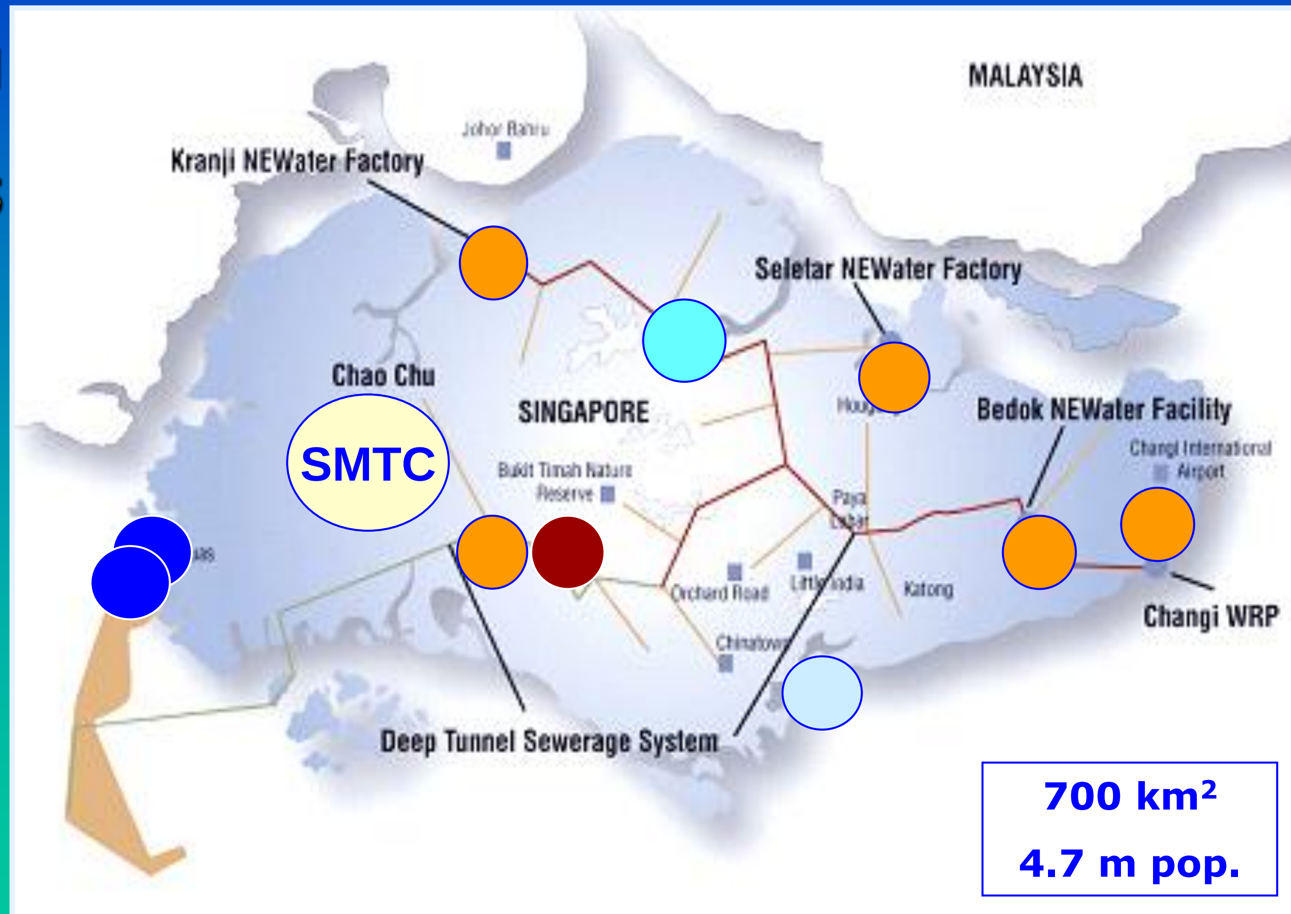
Prof Anthony Fane & Assoc Prof Wang Rong
Co-Directors

SMTC

Singapore Membrane Technology Centre

Singapore
- a world leader in membranes & the water industry

- Water 274ML/d
- Desalination 455
- NeWater 500
- Wastewater MBR 23
- Barrage



> Megaton per day passing through membranes

SMTC Overview

Funded by EDB/NTU/EWI (NRF)/Industry ~S$38m

- **Research & development**

~ *Membranes. Fundamental & applied research.*
Environmental & Water Technologies.

- **Education & Training**

~ *Manpower.*

~ *Outreach to the region.*

- **Industry & Application**

~ *Incubator for novel technology applications in EWT.*

Full-time (equivalent) > 85 researchers

Fundamental Generic Topics

- Membranes
- Modules
- Fouling
- Processes
- Characterization
- Modeling etc

6 Themes

- Water Production
- Water Reclamation
- Wastewater MBRs
- Energy Issues
- Sensors & Monitoring
- Special Needs

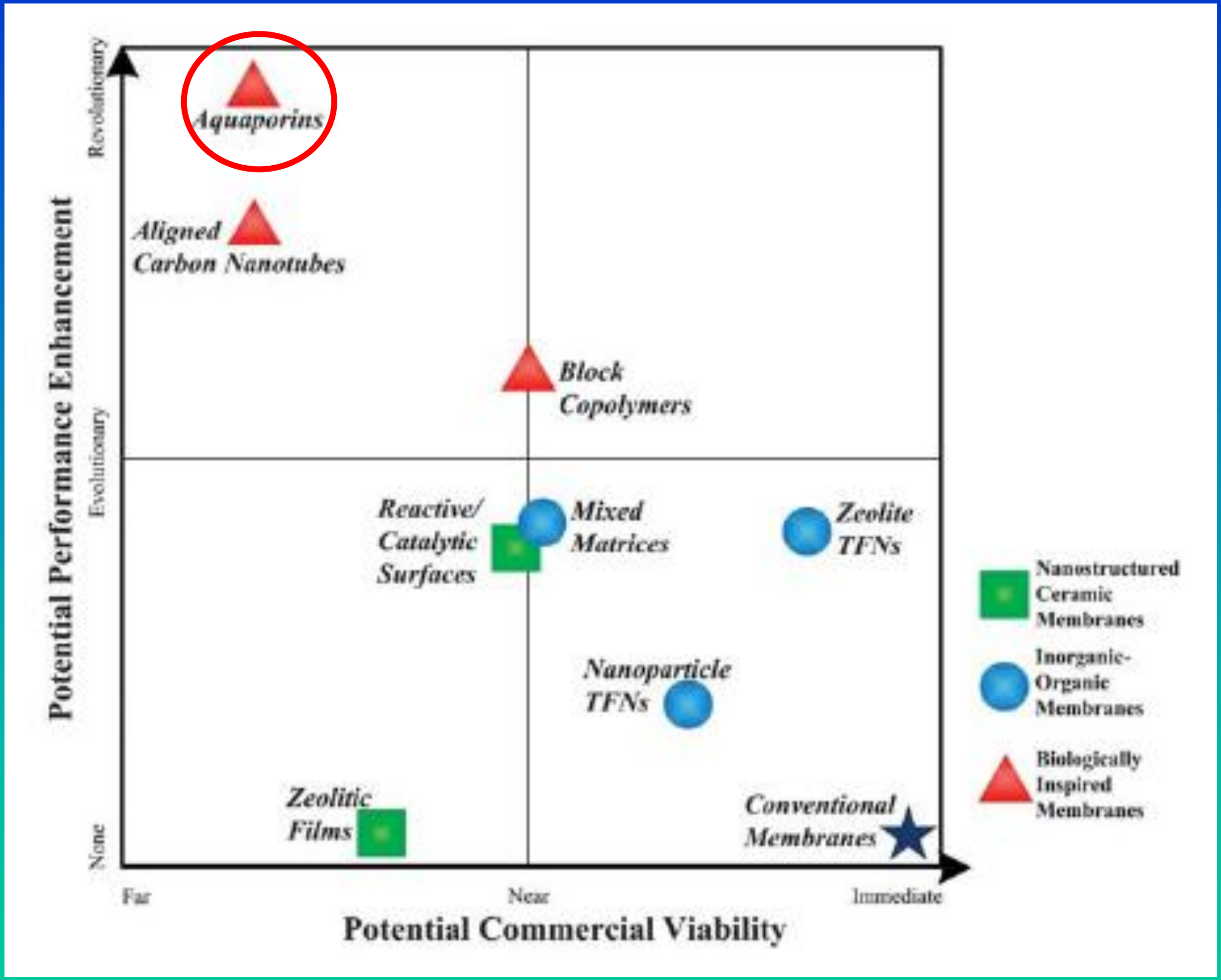
Outline

- Reverse Osmosis
  - Novel membranes/modules
  - Cascade design
  - Biofouling
- Forward Osmosis
  - Novel membranes/modules
  - PRO (osmotic power)
- Membrane Distillation
  - Novel membranes/modules
  - MDC
- Sensors & Monitoring

SMTC Research not on today's Agenda

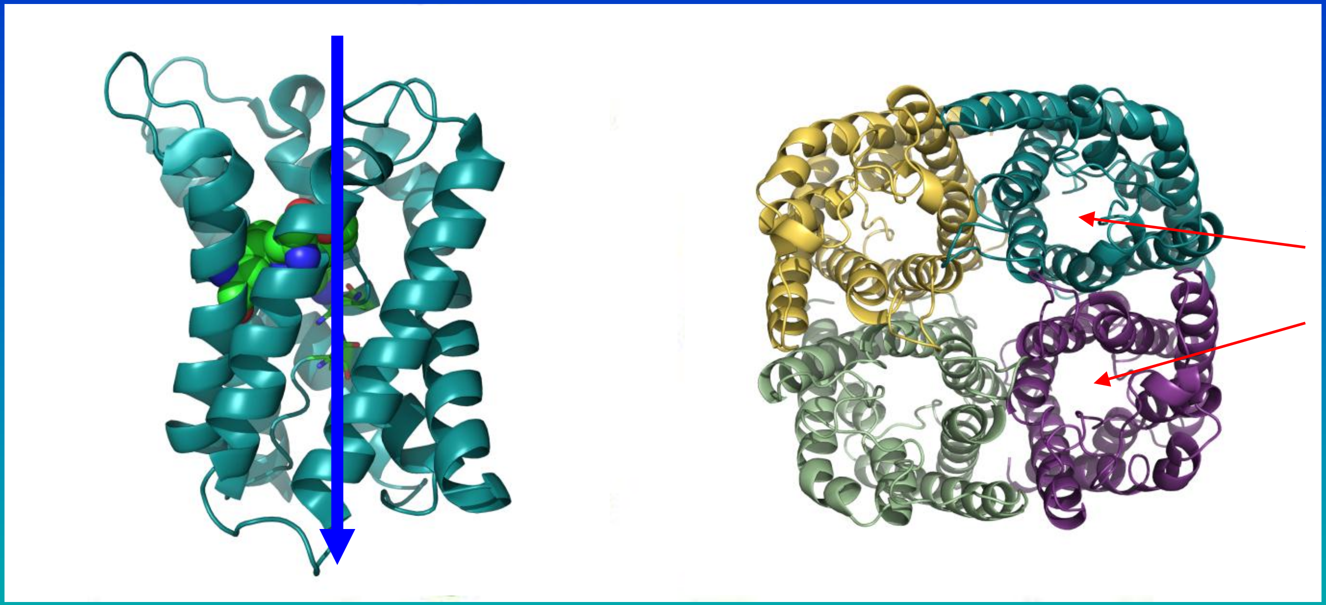
- **Low Pressure (MF,UF, NF)**
  - Novel membanes
  - Fouling control
  - Bubbles/vibrations/ultrasound
  - Gravity driven (low energy)
- **Membrane Bioreactors**
  - MBR fouling control
  - High retention MBRs (FOMBR, MDBR)
  - Extractive MBR
  - Anaerobic fluidized bed MBR
- **Membranes for Special Needs**
  - Hydrogel/cryogel 'integral' membranes for WT
- **Life Cycle Assessment**
  - RO desalination options

The Quest for 'Super flux' RO membranes



Pendergast & Hoek, Energy & Env.Sci. (2011), 4, 1946-1971

Biomimetic RO Membranes



Water channels

Aquaporin

Aquaporin Tetramer

Aquaporins are pore-forming membrane proteins.

High water permeability- low salt transmission.

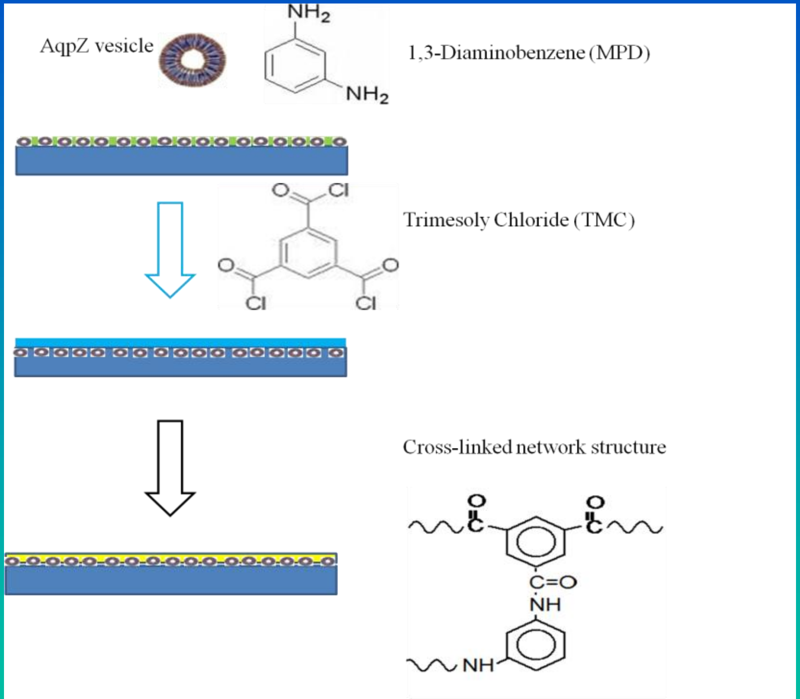
Basis for desalination membranes ?

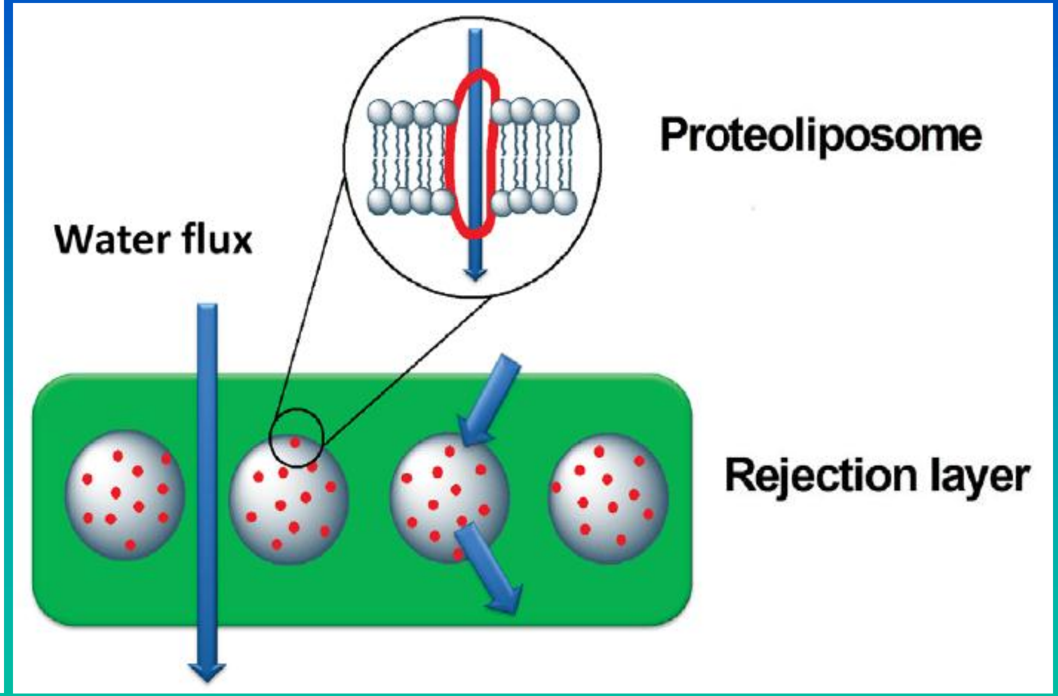
M.Kumar et al., PNAS (2007), 104, p 20719-

Biomimetic RO Membrane

- TFC incorporating AqP vescicles

[EWI project 0804-IRIS-02]



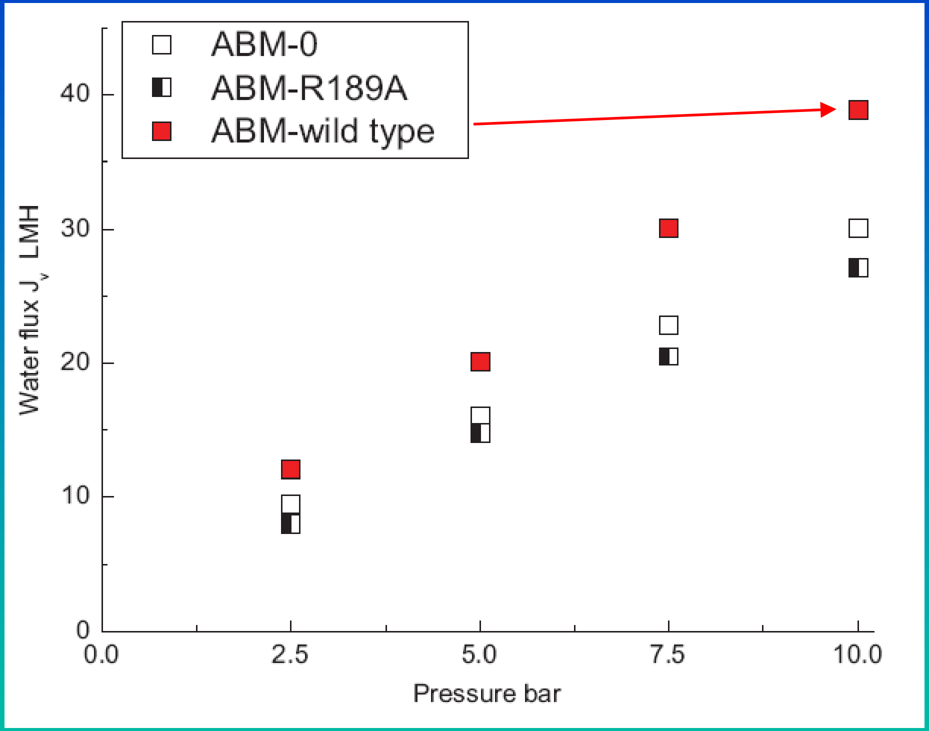


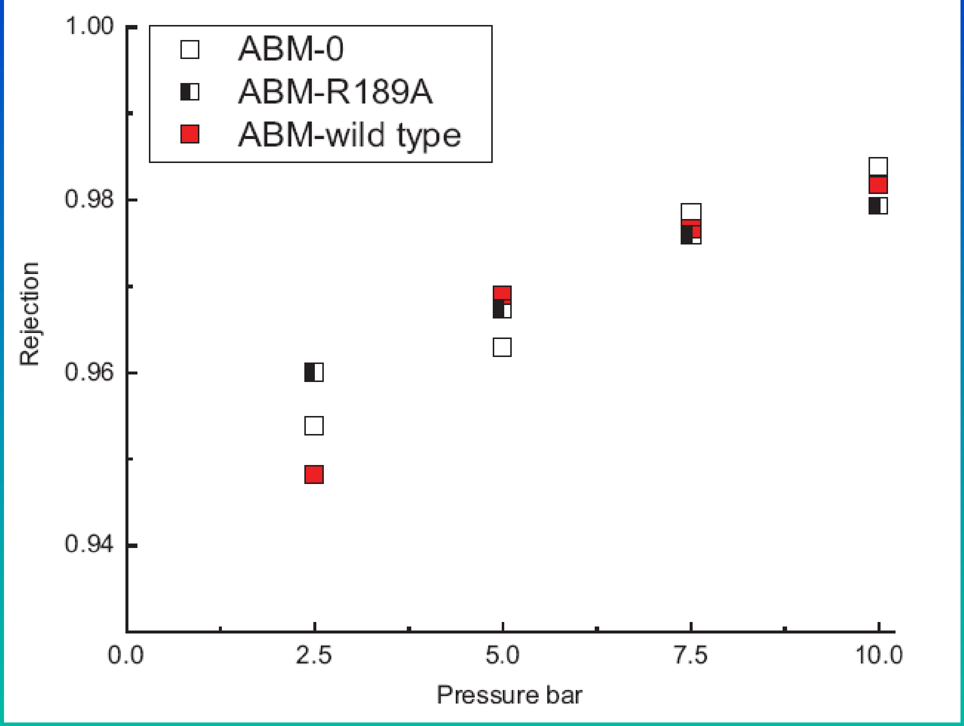
CY Tang et al., AqP-based TFC membrane. US Provisional Patent (2011)

Y Zhao et al., Synthesis of Robust & High-performance AqP-based RO, *J Memb. Sci*. (2012)

CY Tang et al. Desalination by biomimetic AqP: Review of status. *Desalination,308* (2013)

Biomimetic RO Membranes with Aquaporin incorporated

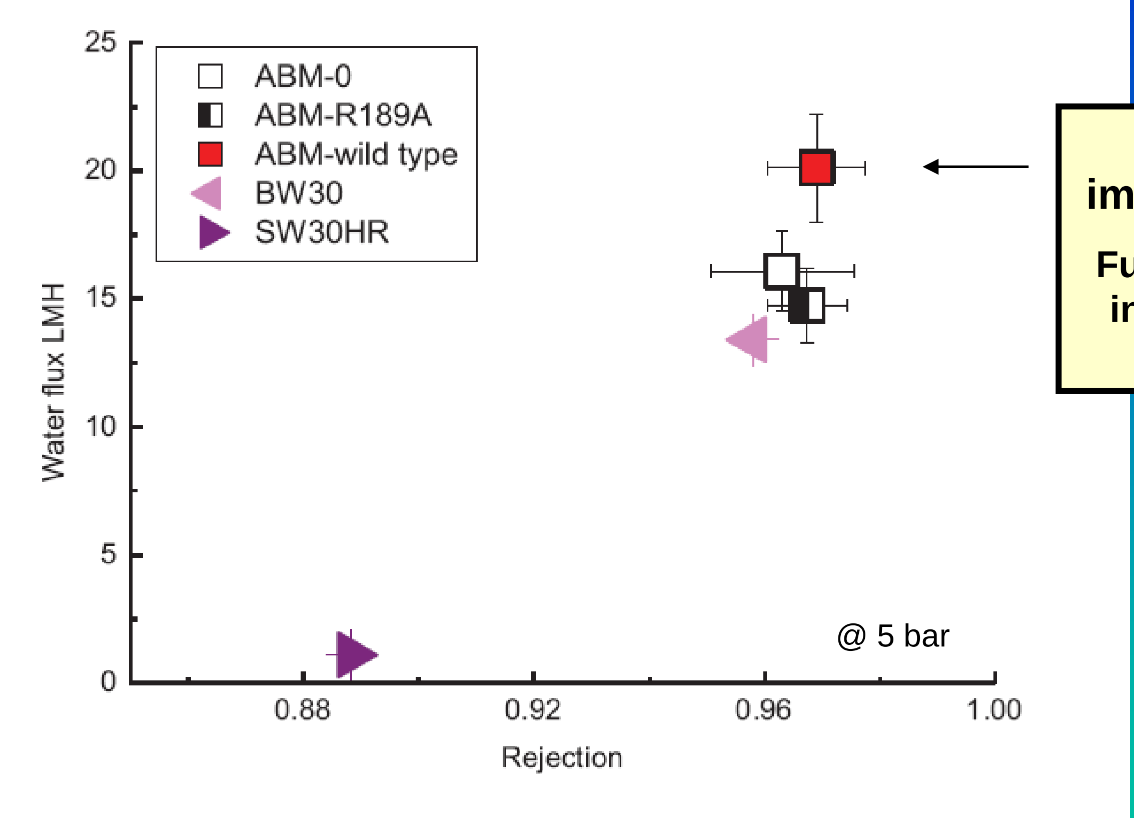




Water flux **Rejection**

RO with Aqp Z wild type has higher flux and similar rejection.

Biomimetic RO Membranes with Aquaporin incorporated



~ 50% improvement.

Future work to increase Aqp content.

Aquaporin Inside™ RO/FO Membranes - patent pending

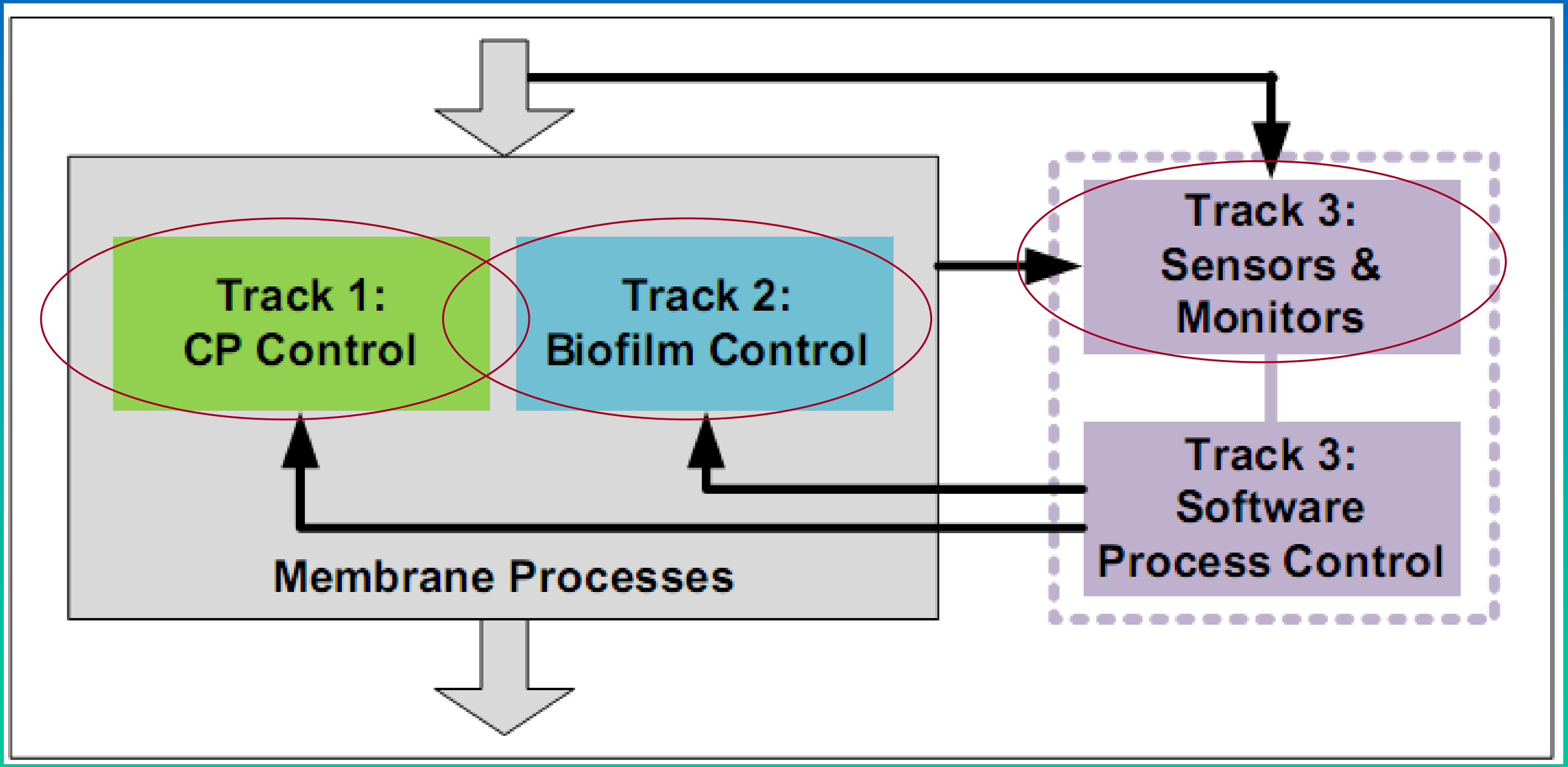
Commercialization through Aquaporin Asia P L.

ABM-wt superior based on t-Test analysis (>99% confidence). Based on 4-8 independent samples

[EWI project 0804-IRIS-02]

Improving the efficiency of membranes in the Water Industry

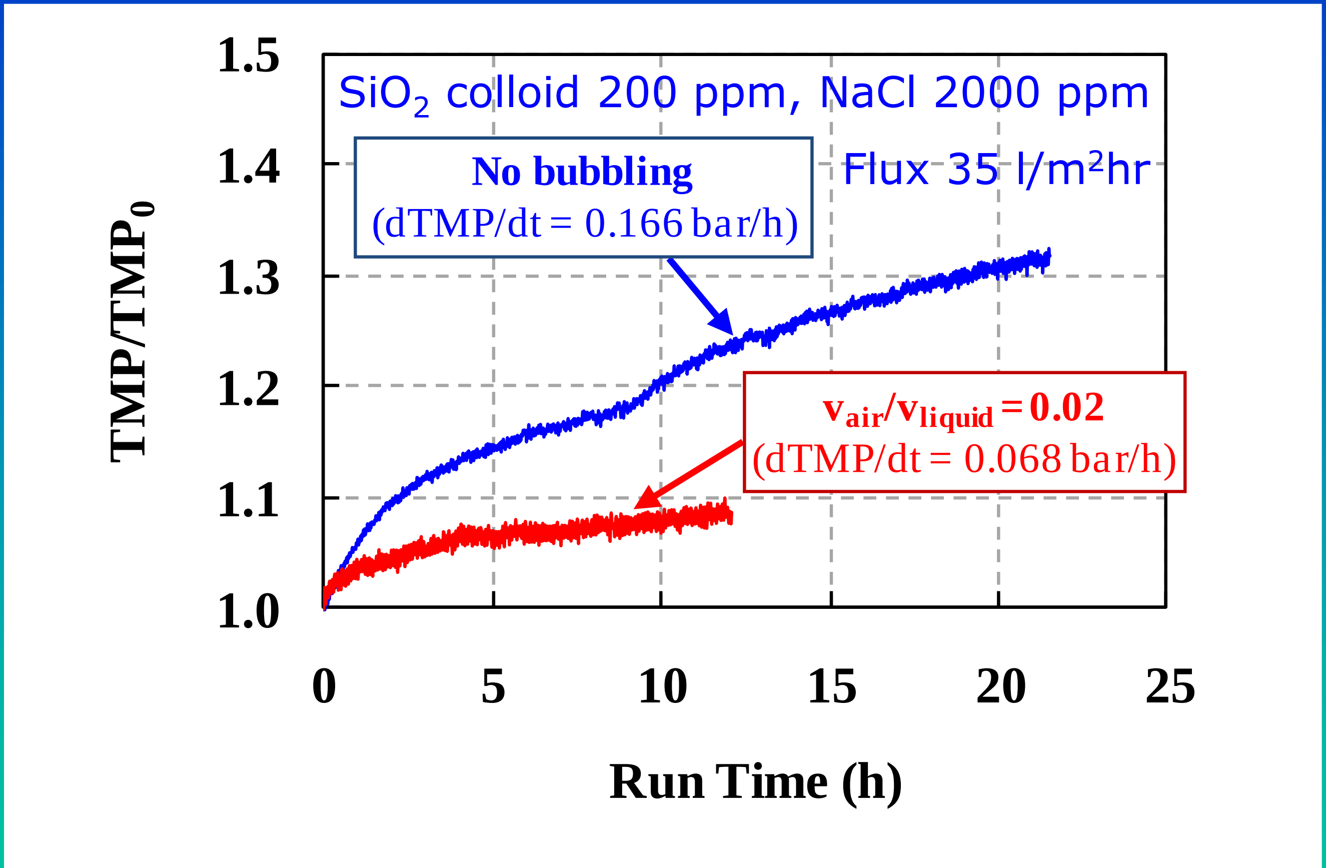
The quest for 'new generation' high performance membranes will come to nothing unless we can develop new paradigms for control of CP and fouling



(EWI RPC 0901)

Fouling control ~ unsteady shear stress

RO ~ With & without bubbly flow



- Two-phase flow reduced rate of fouling by 60%
- Is there an optimal air-liquid ratio , bubble size etc ?

(EWI RPC 0901-03-02)

Outline

- Reverse Osmosis
  - Novel membanes/modules
  - Cascade design
  - Biofouling
- Forward Osmosis
  - Novel membranes/modules
  - PRO (osmotic power)
- Membrane Distillation
  - Novel membranes/modules
  - MDC
- Sensors & Monitoring

Forward Osmosis

Membrane Distillation

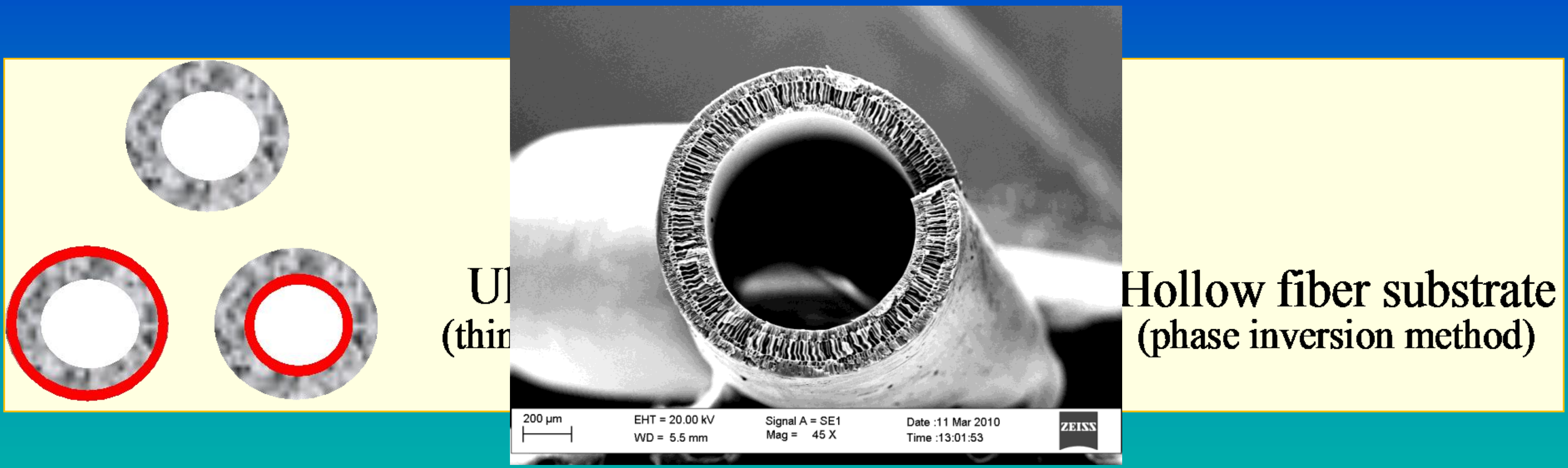
- Atmospheric pressure membrane processes.
- Can use waste or solar heat (low GHG options).
- Osmotic gradients (FO)

Needs:

- Specialized membranes.
- Optimization of module design and operation.

FO Thin Film Composite Hollow Fibers by Interfacial Polymerization

- Need RO-like skin on a thin and porous substrate



- Polyethersulfone (PES) used for tailored substrate.
- Interfacial polymerization chemistry (MPD+TMC-> **RO skin**).

EWI Project

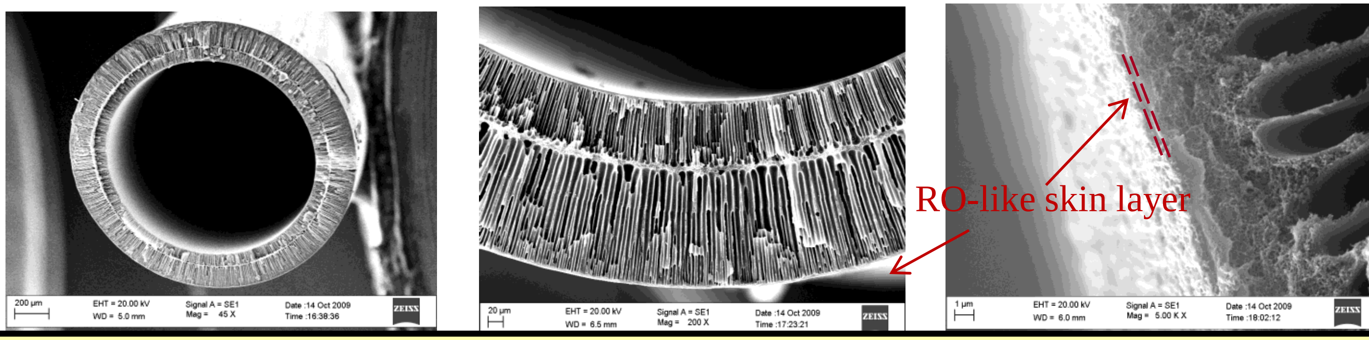
0801-IRIS-05

Wang,R. et al. J.Memb.Sci., 355, (2010)
Chou,S. et al. Desal., 261, (2010)
Shi,L. et al. J.Memb.Sci., 382 (2011)
Qiu,C. et al. Desal, 287 (2012)
Setawan,L. et al. J.Memb. Sci, 394 (2012)

Thin Film Composite FO Hollow Fibers

(RO-like skin layer + UF-like skin layer)

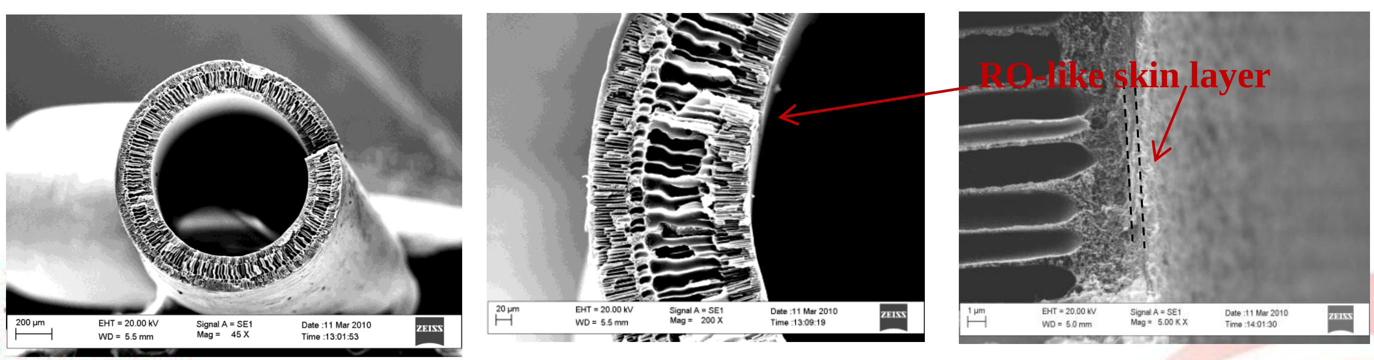
#A



JMS, 355 (2010) , 158–167

Sample	Water flux ($L/m^2.hr$)	Solute flux /water flux (g/L)	Draw solution	feed
#A-FO hollow fiber	**12.9**	**0.39**	0.5 M NaCl	DI water
#B-FO hollow fiber	**32.2**	**0.11**	0.5 M NaCl	DI water
#C-FO hollow fiber	**42.6**	**0.094**	0.5 M NaCl	DI water

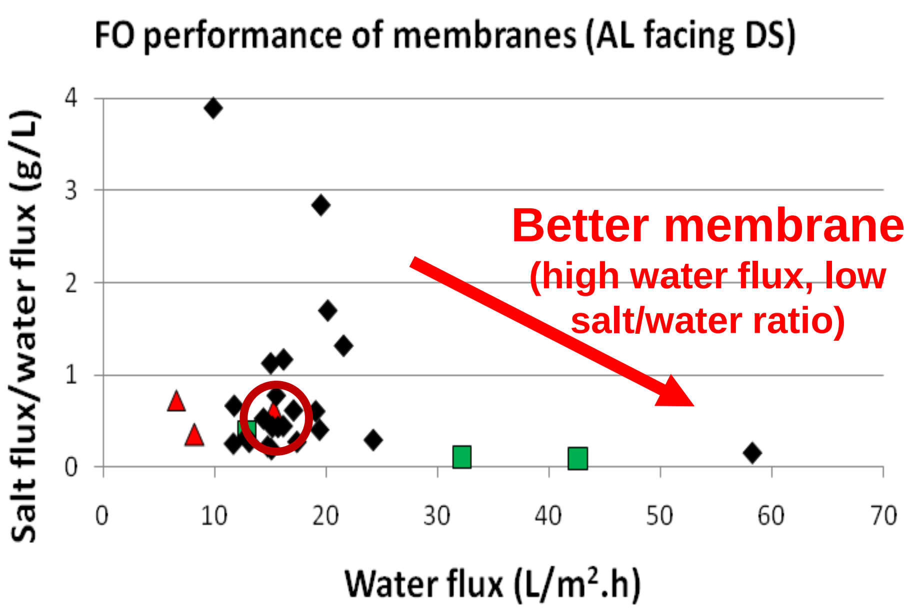
#C

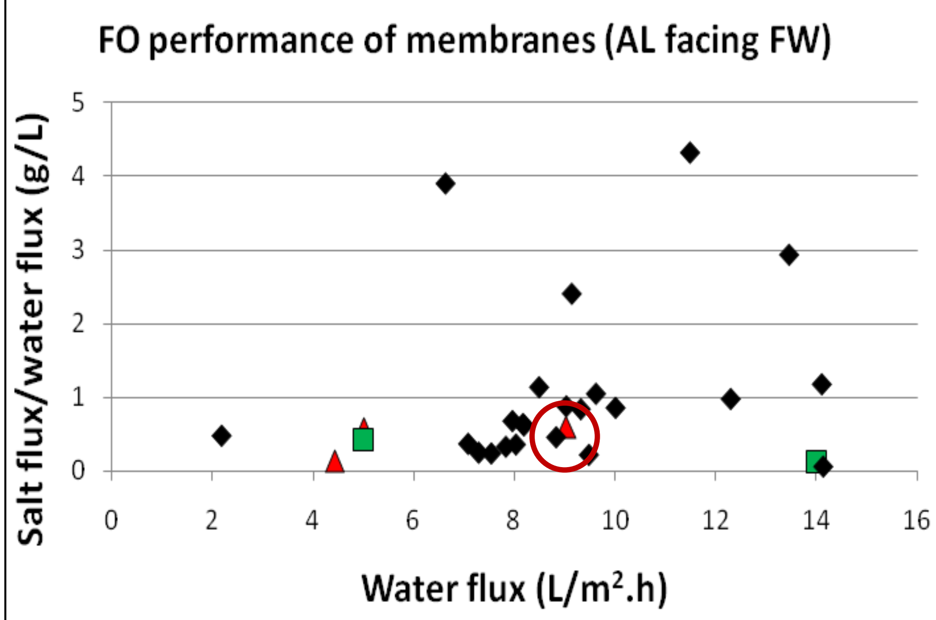


Desalination, 61 (2010) 365–372

Performance of SMTC FO membranes

Hollow Fibres and Flat Sheets





HTI FO membrane Commercial

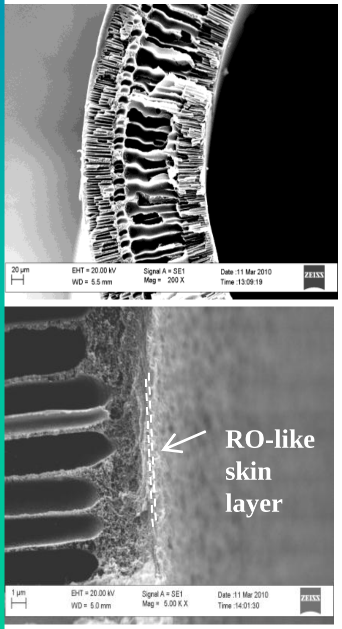
TFC hollow fiber FO membrane SMTC

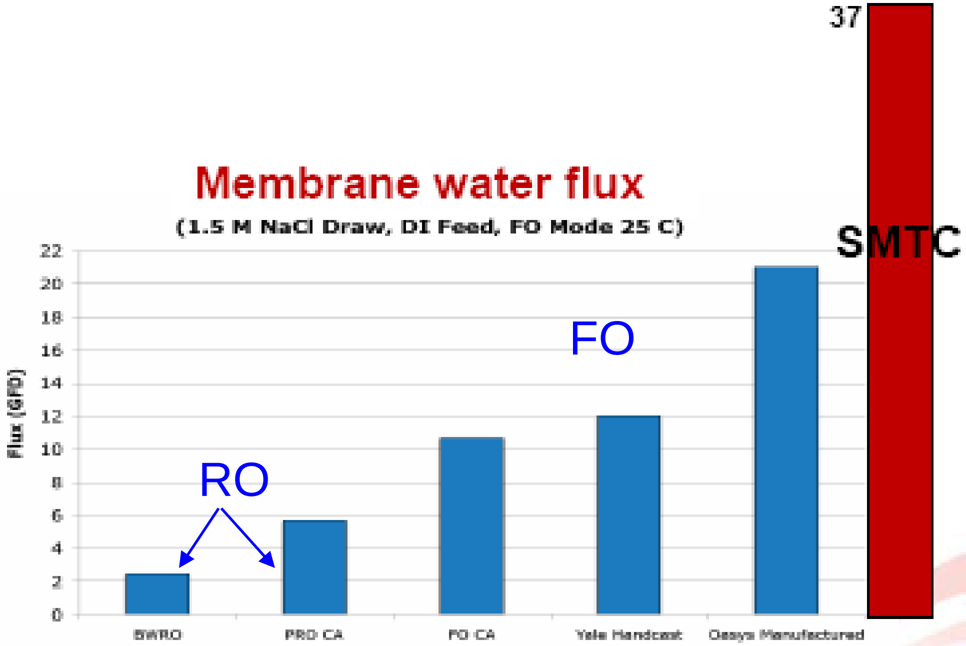
TFC flat-sheet FO membrane SMTC

Membranes developed in SMTC have substantially better performance than available commercial FO membranes.

Novel Hollow Fibre FO Membrane Performance

Water flux ($L/m^2.hr$)	Draw solution	Feed	Applications
42.6	0.5 M NaCl	DI water	
32.9	0.5 M NaCl	500ppm	Wastewater
24.2	2 M NaCl	1 wt% (~0.17 M)	Food processing
12.4	2 M NaCl	3.5 wt% (~0.59M)	Seawater





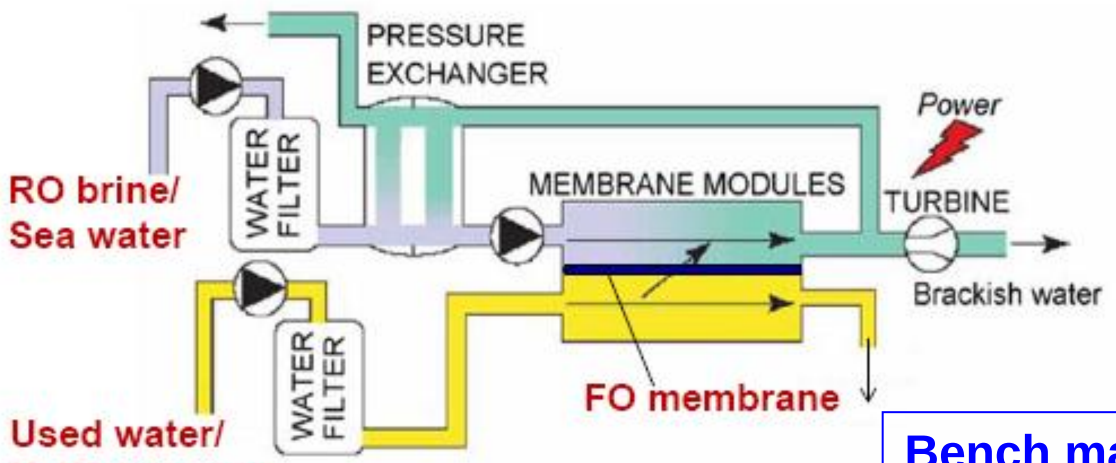
Wang Rong et al. SMTC

Source of data: Rob McGinnis, *July 11, 2010*

Potential Applications of FO

Applications	Potential Benefits	Needs
Immediate applications if FO membrane is available		
Pressure Retarded Osmosis (PRO)	❑ **Power generation**	❑ Membrane ❑ Draw (brine, seawater)
FO concentration /dewatering (food, pharmaceutical processing)	❑ **Low energy process** ❑ **No temperature detrimental effect**	❑ Membrane ❑ Draw (brine, seawater)
Applications if FO membrane & draw solute are available		
FO desalination	❑ **Lower energy desalination**	❑ Membrane ❑ **Draw solution regeneration**
FO bioreactor	❑ **High quality product water**	❑ Membrane ❑ **Bioreactor** ❑ **Draw solution regeneration**

Pressure-retarded Osmosis



Adapted form Desalination 224 (2008) 64–70

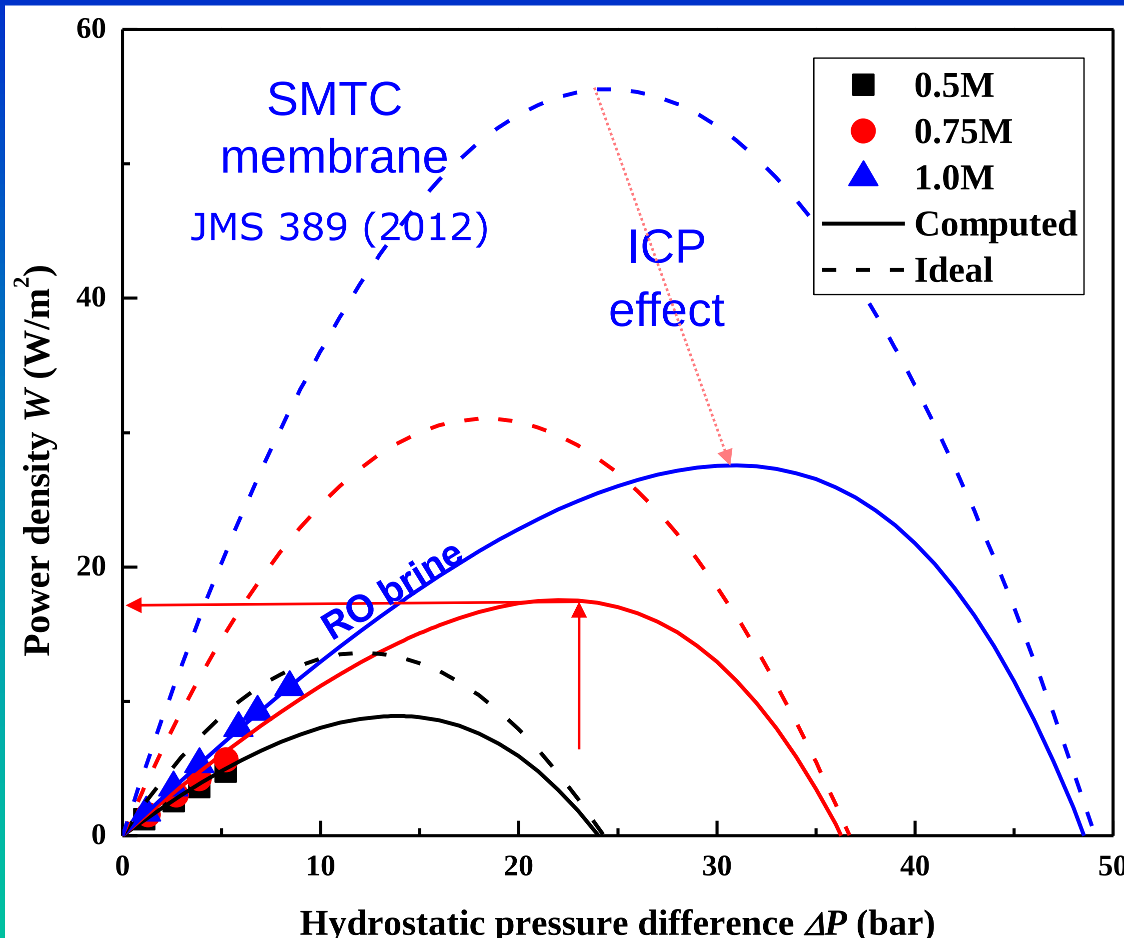
Statkraft

Bench mark is 5W/m²

Uses 'osmotic power' of **sea water or RO brine** in contact with **NeWater brine etc** via FO membrane to increase flow of pressurized feed.

Membrane	Feed	Draw Solution	Hydraulic pressure (bar)	Power density (W/m²)	Reference
Hollow fiber	10mM NaCl (wastewater)	0.5M NaCl (sea water)	5.0	4.0	SMTC (latest)
		1.0M NaCl (RO brine)	8.8	11.2	Chou, Wang et al., (2012), JMS, 389
	40mM NaCl (NeWater brine)	0.5M NaCl (sea water)	8.9	5.6	
		1.0M NaCl (RO brine)	9.0	10.6	

Pressure-retarded Osmosis



Needs:

FO membrane @ 25 bar & low fouling

Power generated from SWRO brine ~ 0.3 - 0.5 kWh/m^3 brine

Uses: - reduce the net energy for SWRO plant, or

- run 'NeWater' plant in parallel.

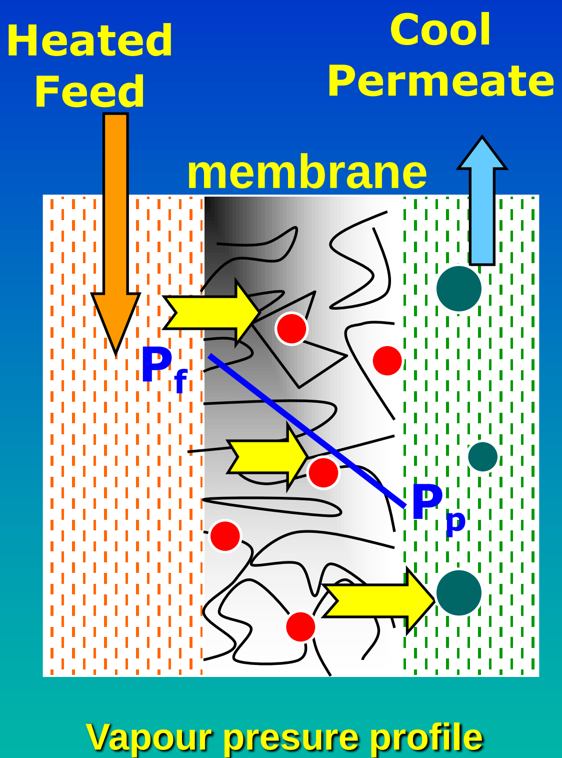
The cost : PRO plant of 100,000m^2 for 100 ML/day of brine

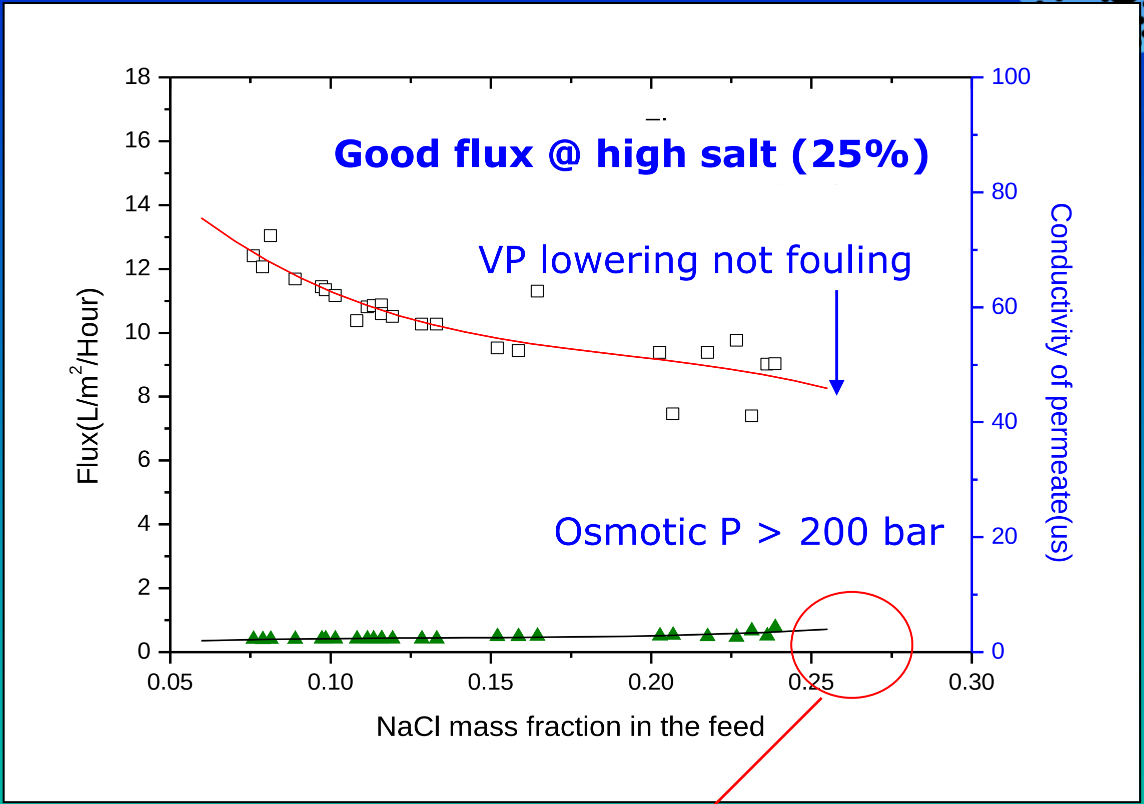
Outline

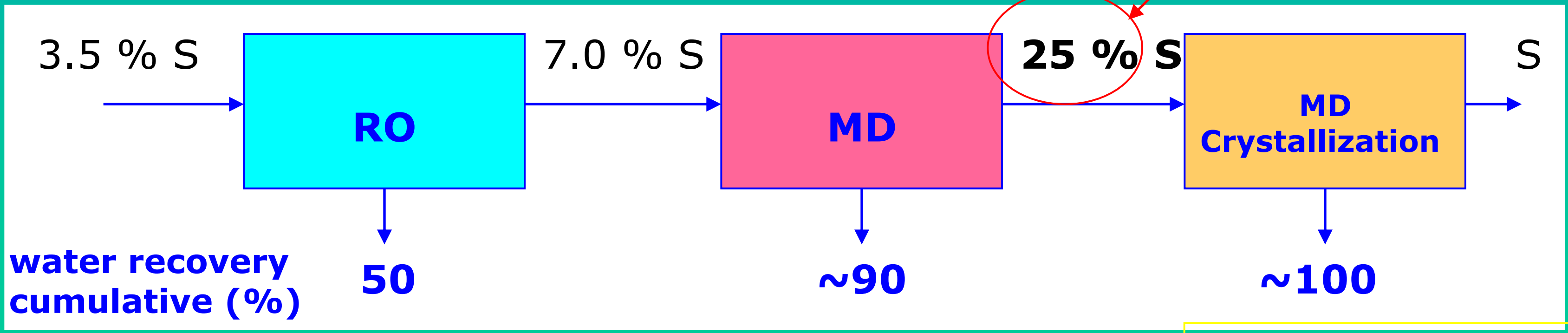
- Reverse Osmosis
  - Novel membanes/modules
  - Cascade design
  - Biofouling
- Forward Osmosis
  - Novel membranes/modules
  - PRO (osmotic power)
- **Membrane Distillation**
  - **Novel membranes/modules**
  - **MDC**
- Sensors & Monitoring

Membrane Distillation

(Water vapour transport through hydrophobic membrane)

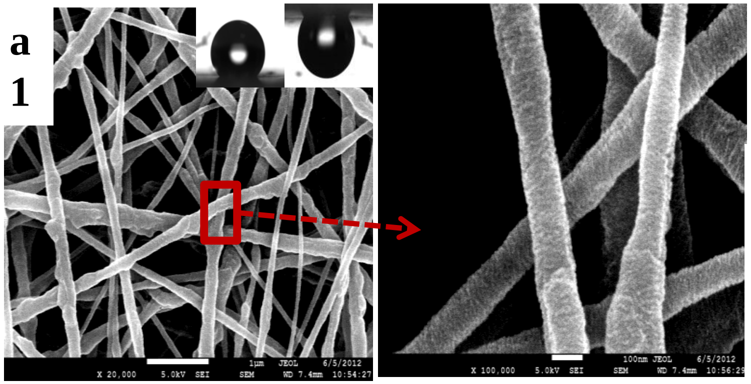




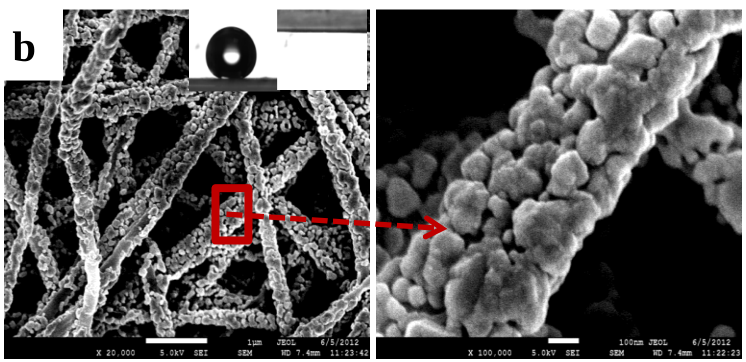


Novel MD Membranes

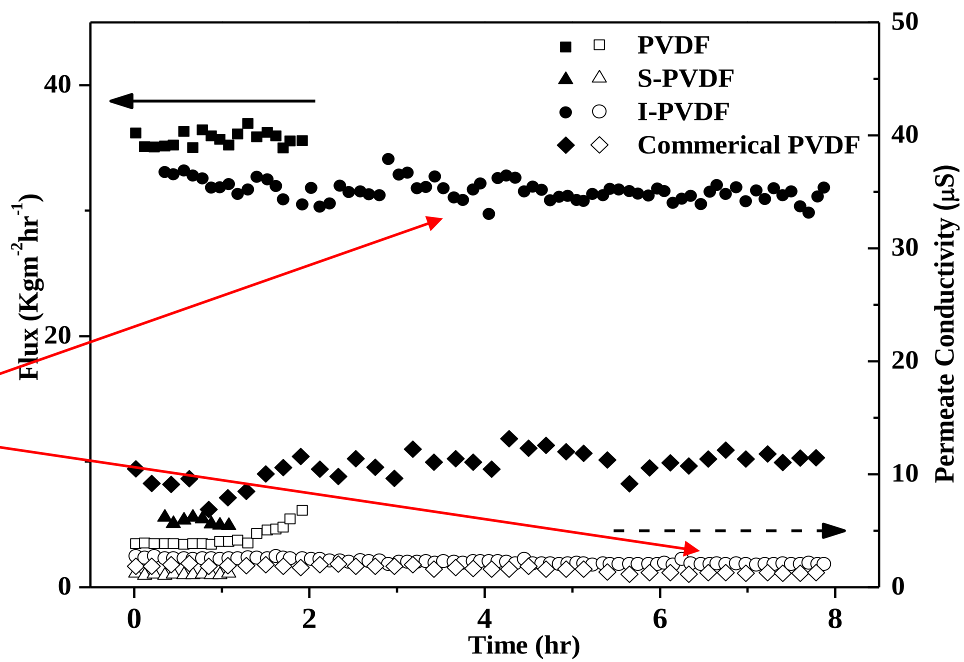
PVDF nanofiber



Nanoparticle coating



Electrospun with nanoparticle coating is super hydrophobic (Contact angle = 153 deg),with good flux and no wetting.

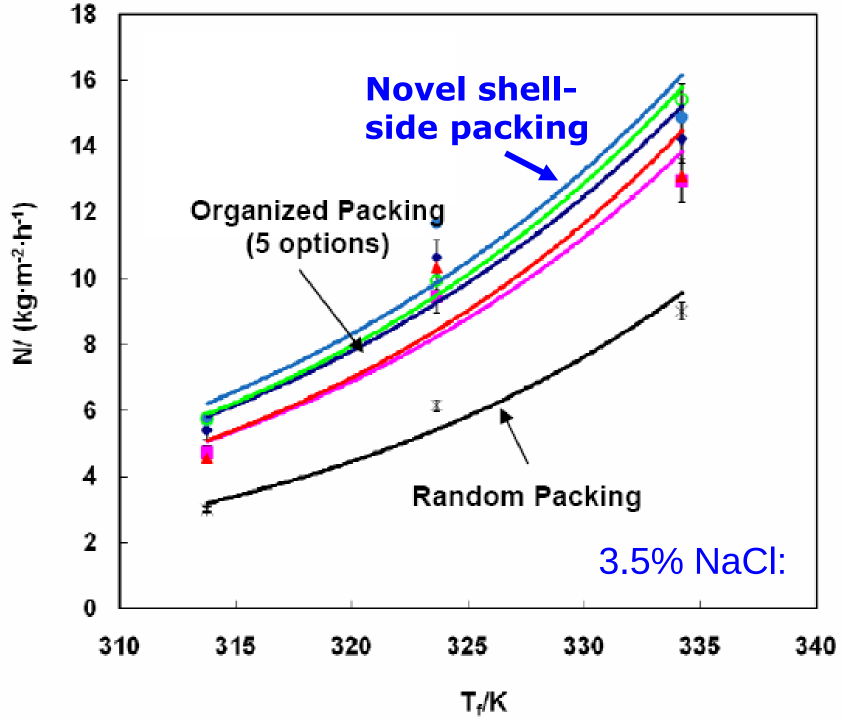


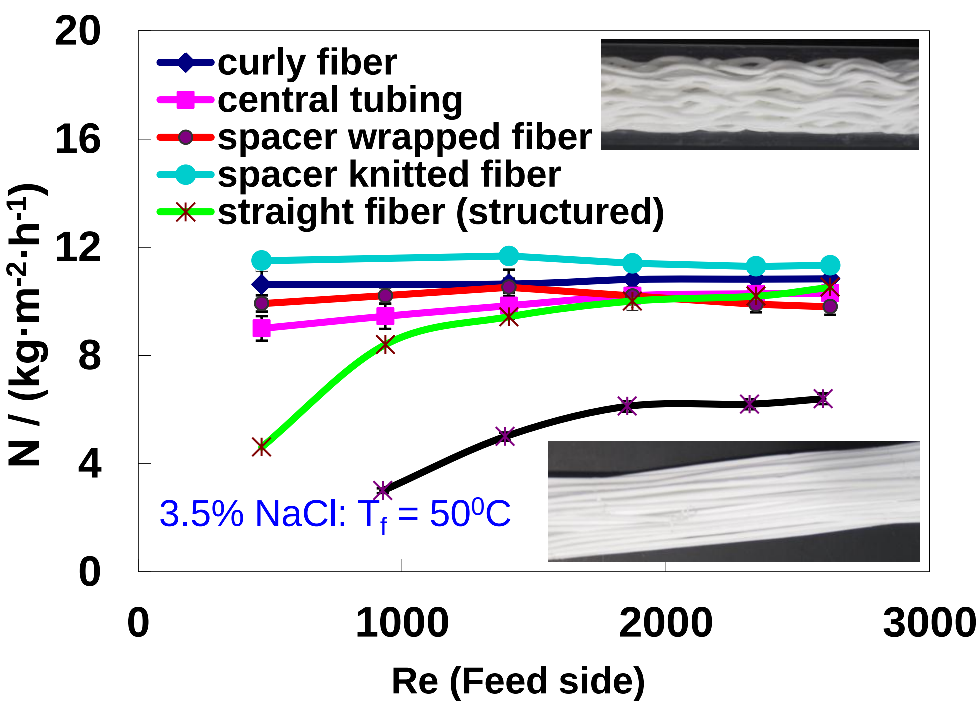
Liao et al. JMS 425 (2013)

EWI Project 0901-02-03

Flux enhancement in MD module

Counter-current with improved shell-side flow



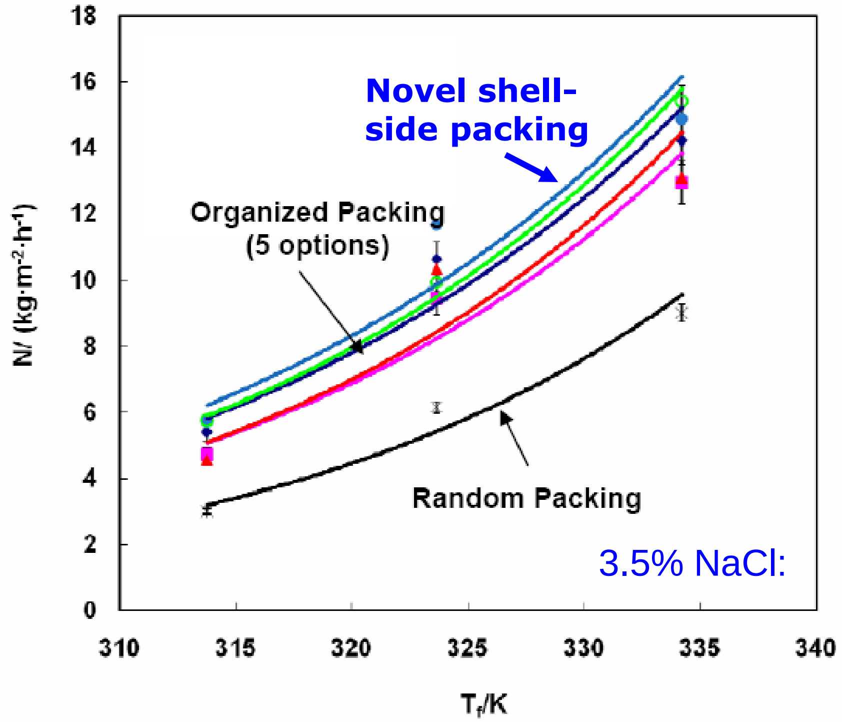


Fibre packing can be optimized to enhance flow distribution & flux (200% improvement vs random)

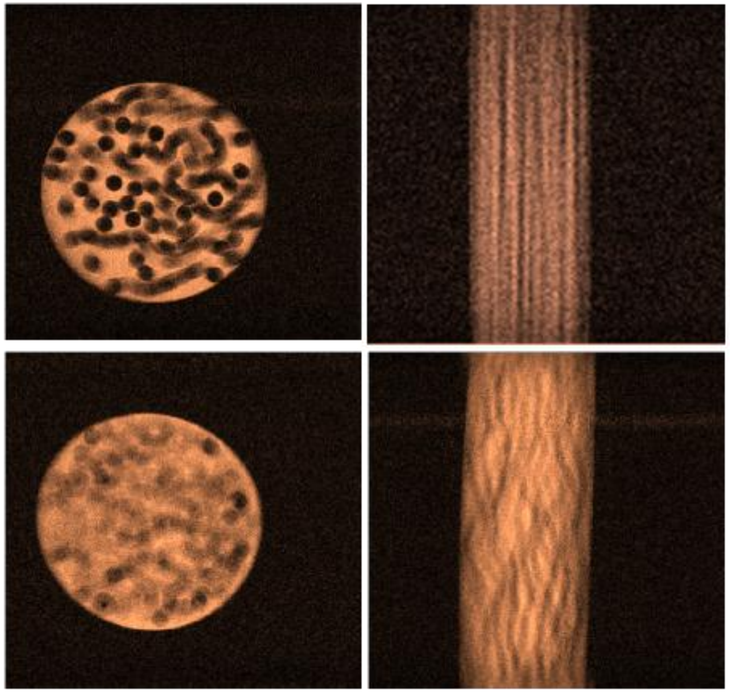
Yang Xing et al. JMS 384 (2011)

Flux enhancement in MD module

Counter-current with improved shell-side flow



NMR Flow Imaging

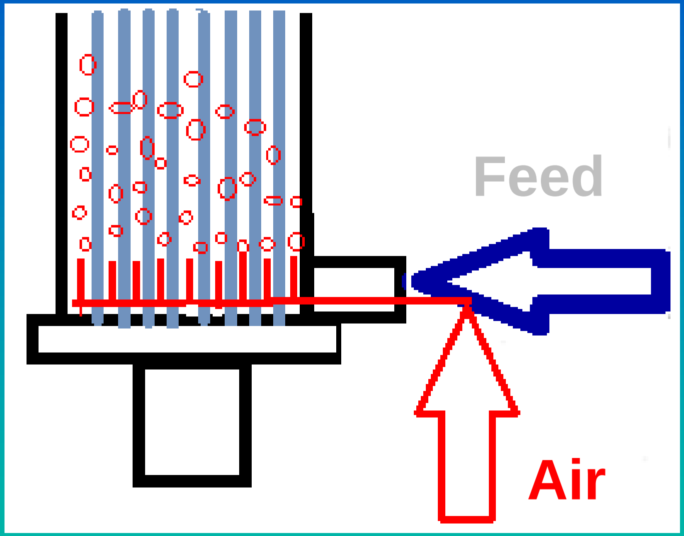


Fibre packing can be optimized to enhance flow distribution & flux (200% improvement vs random)

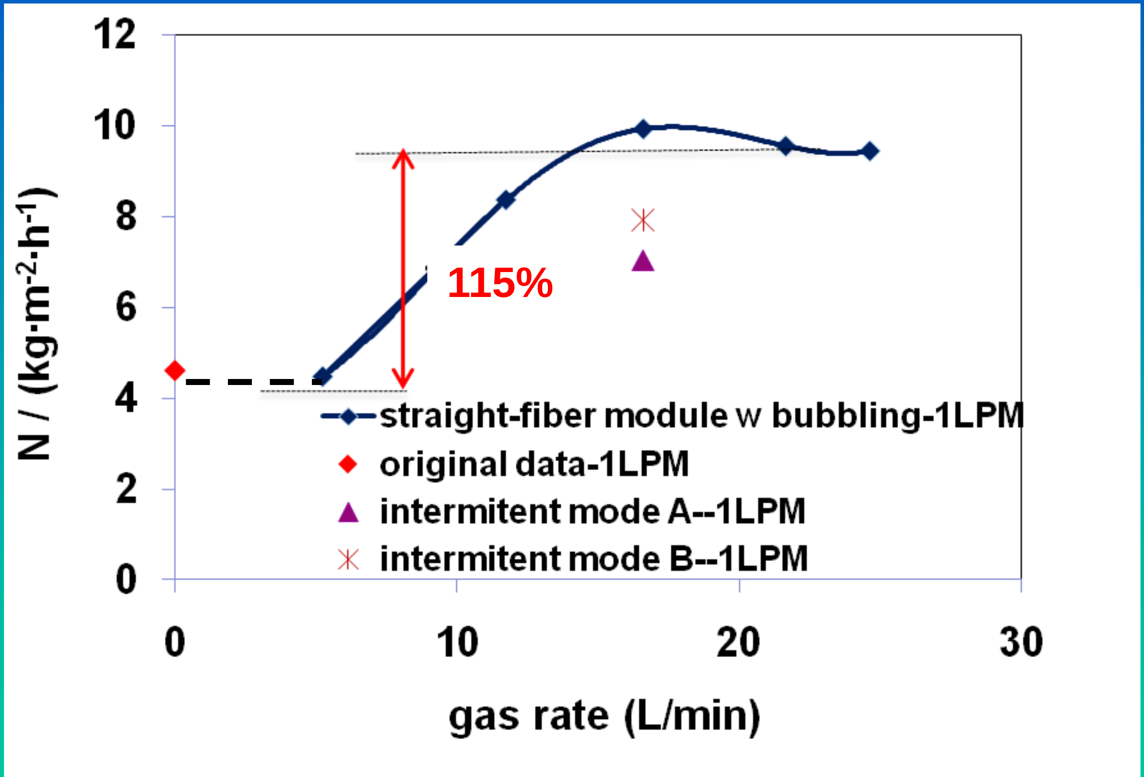
Yang Xing et al. JMS 384 (2011)

Hollow fibre MD modules – Enhanced Flux

Two-phase flow improves flow distribution and shell-side heat transfer coefficient



Bubbling in shell of MD module



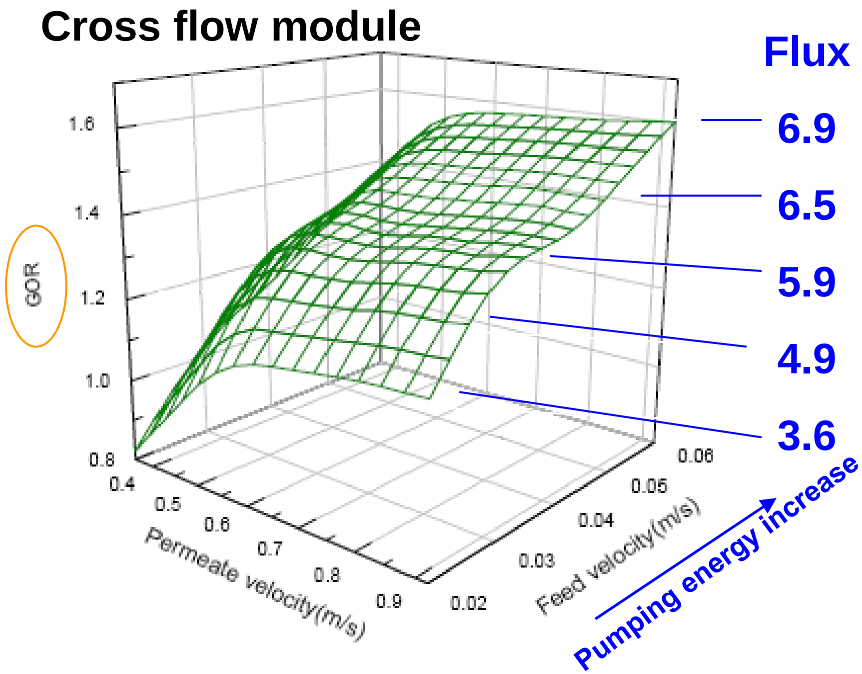
G.Chen et al. Desal 308 (2013)

EWI Project 0901-02-03

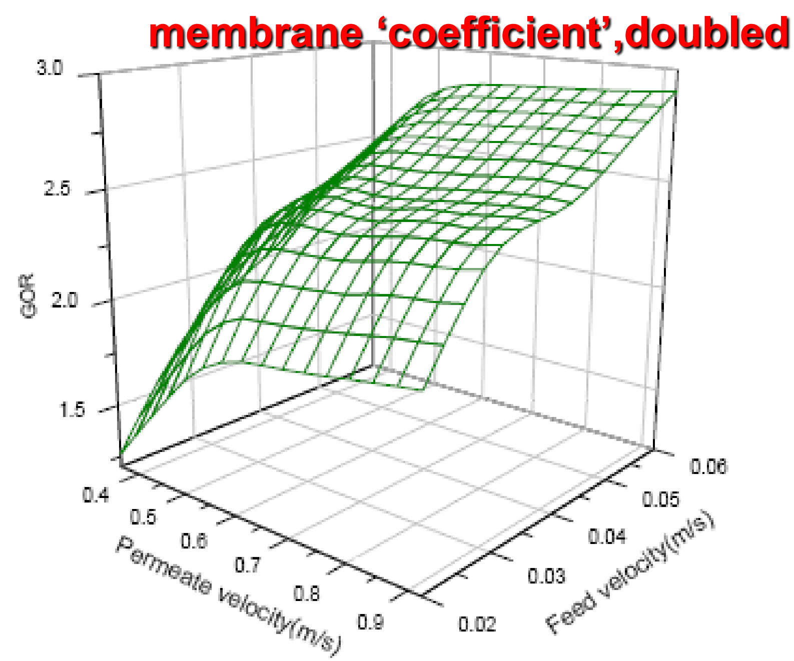
Modelling MD Energy Efficiency.

Factors influencing GOR.

[GOR = kg distillate per kg steam (equivalent)]



Effects of permeate velocity and feed velocity on the GOR (feed temperature: 80 °C, feed concentration: 3.0wt%, permeate temperature: 25 °C, membrane area: $10m^2$)



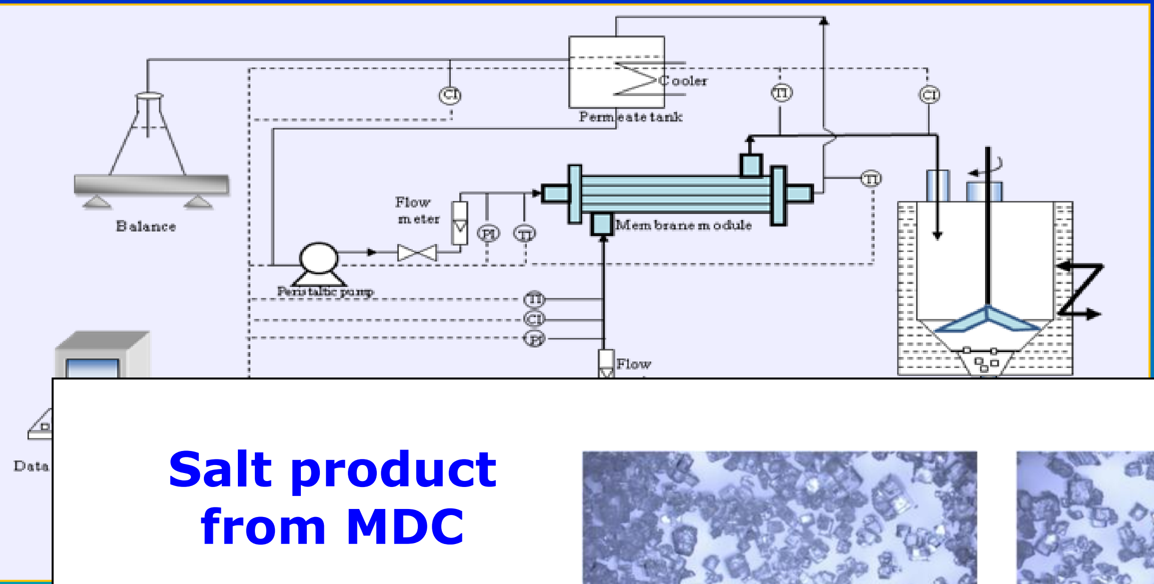
Effects of permeate velocity and feed velocity on the GOR (feed temperature: 80 °C, feed concentration: 3.0wt%, permeate temperature: 25 °C, membrane area: $10m^2$)

GOR increases with feed temps, fluid velocities, module length etc.

GOR increases with membrane 'coefficient', and is *f* (module design, MD mode etc)

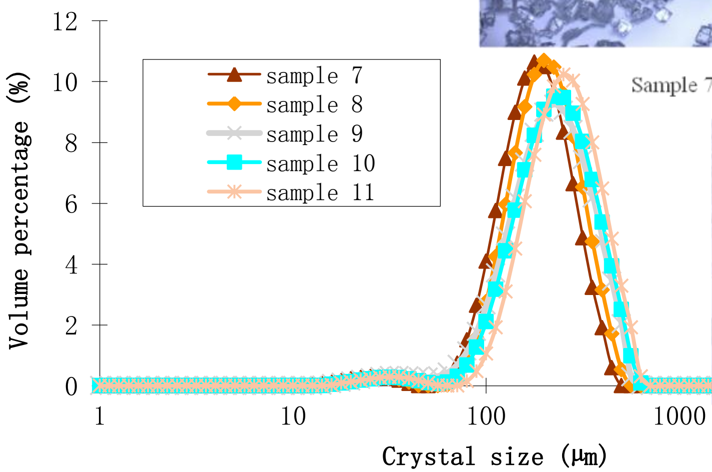
G Zuo et al. Desalination 283 (2011)

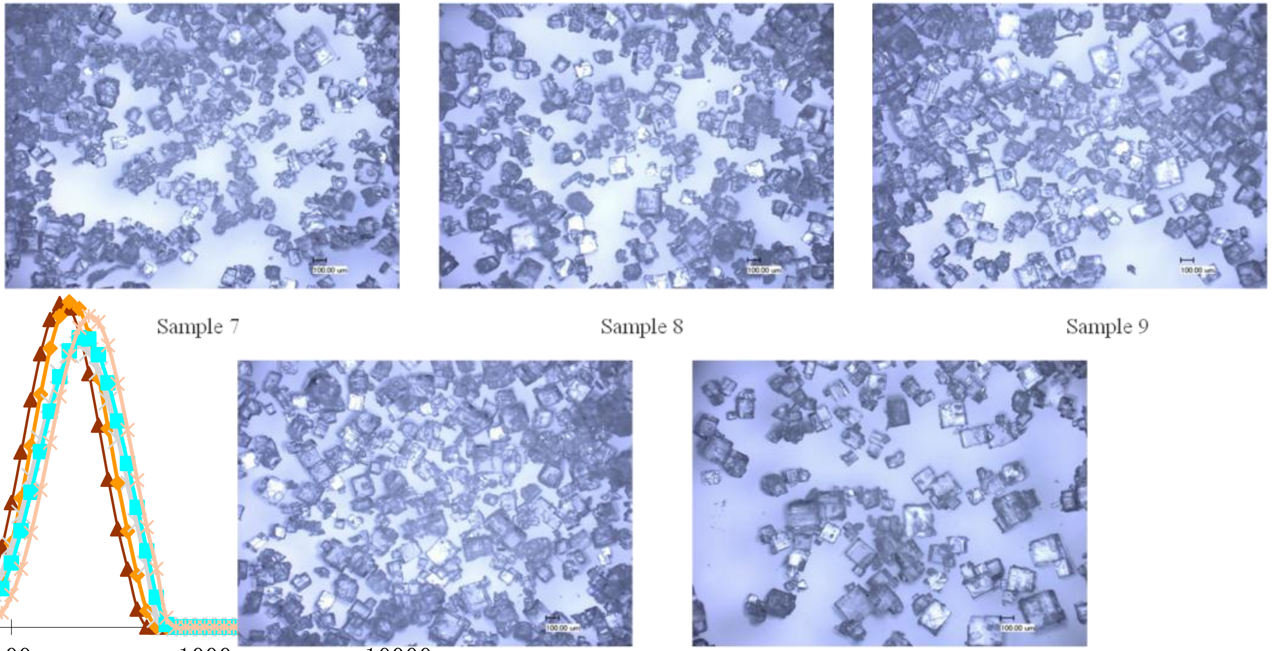
Continuous MD crystallization (CMDC) process with zero discharge



Salt product from MDC

EWI 0901-IRIS-02-03





Sample 7

Sample 8

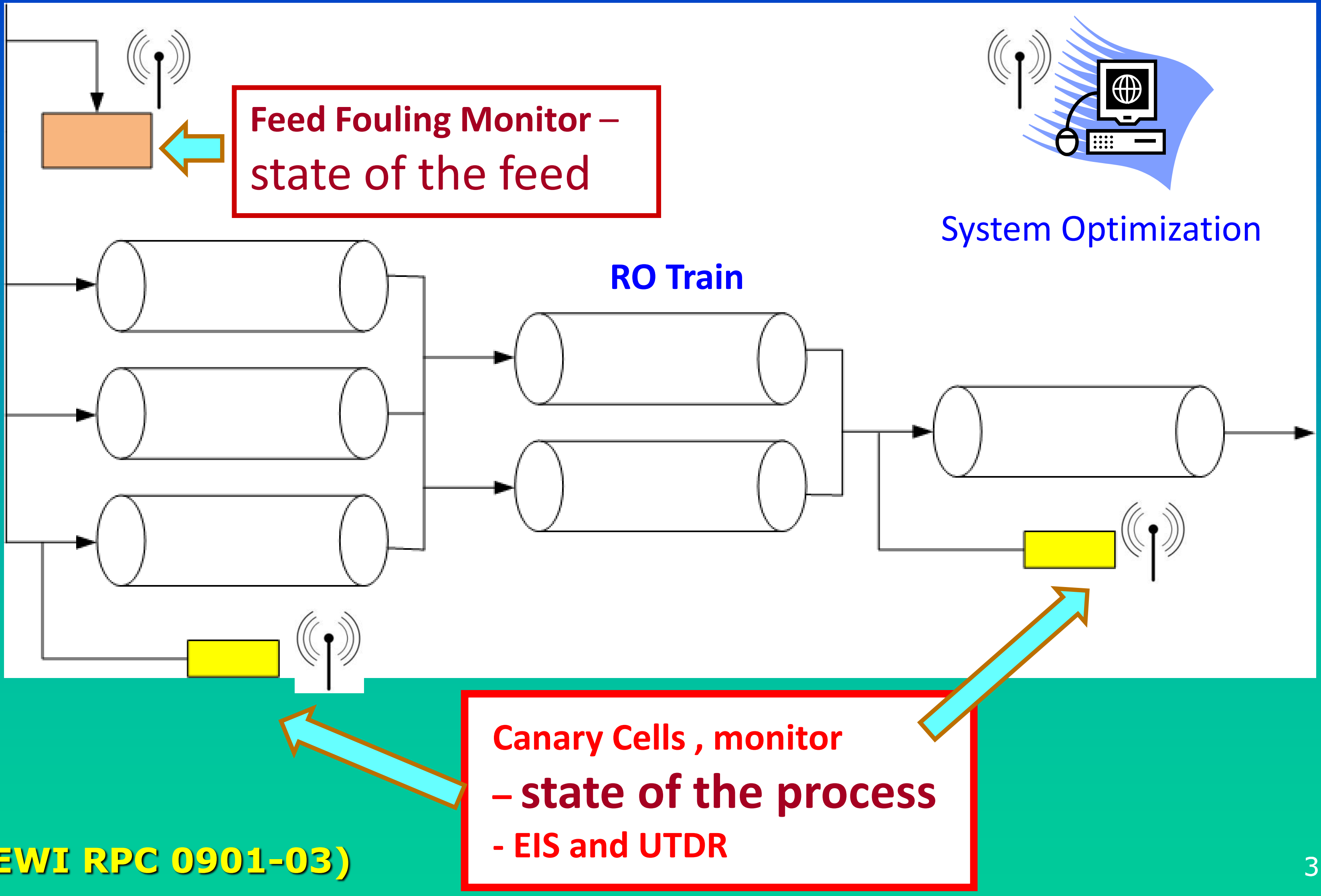
Sample 9

Sample 11

Outline

- Reverse Osmosis
  - Novel membanes/modules
  - Cascade design
  - Biofouling
- Forward Osmosis
  - Novel membranes/modules
  - PRO (osmotic power)
- Membrane Distillation
  - Novel membranes/modules
  - MDC
- Sensors & Monitoring

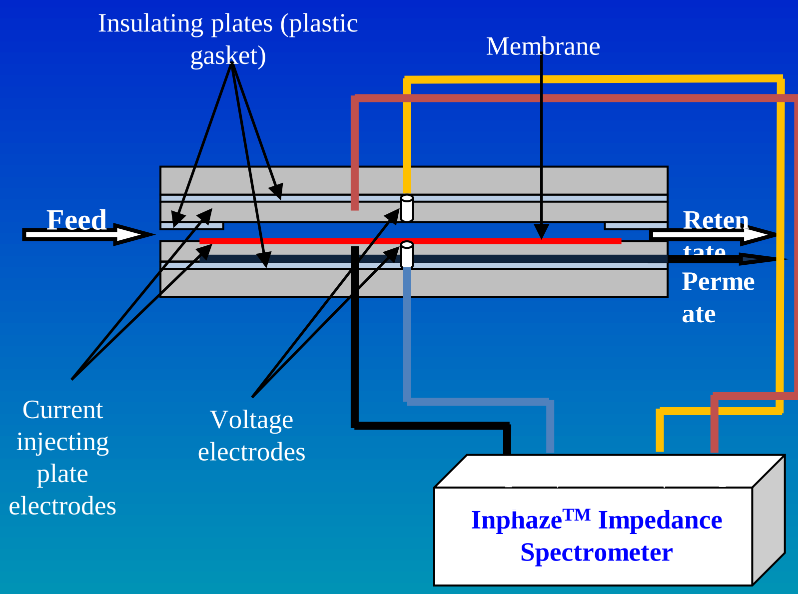
Sensors for Fouling Control in RO

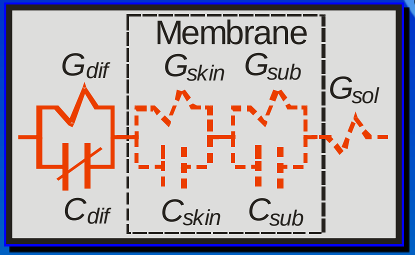


(EWI RPC 0901-03)

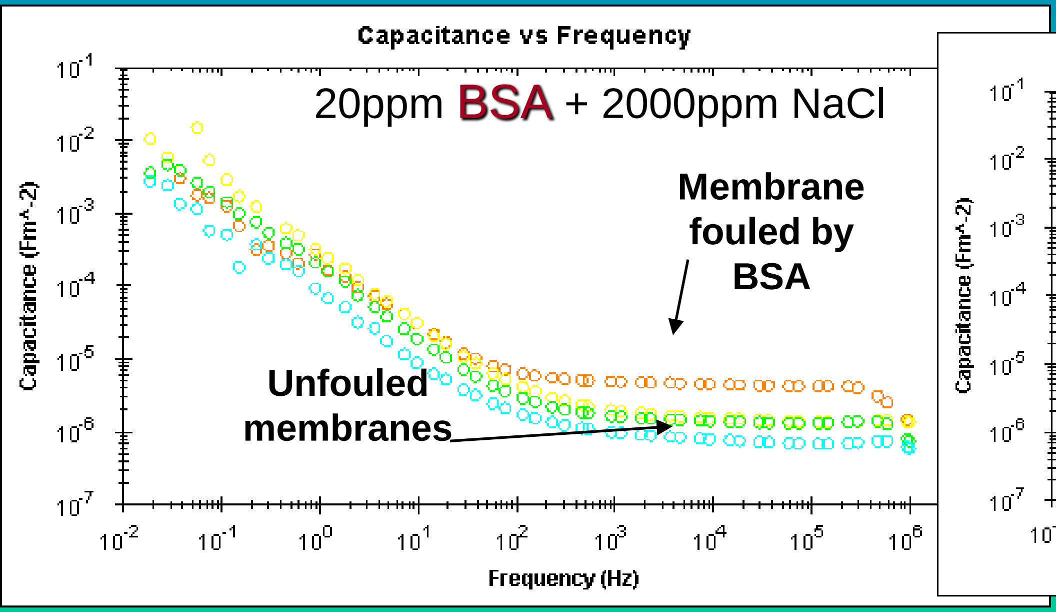
33

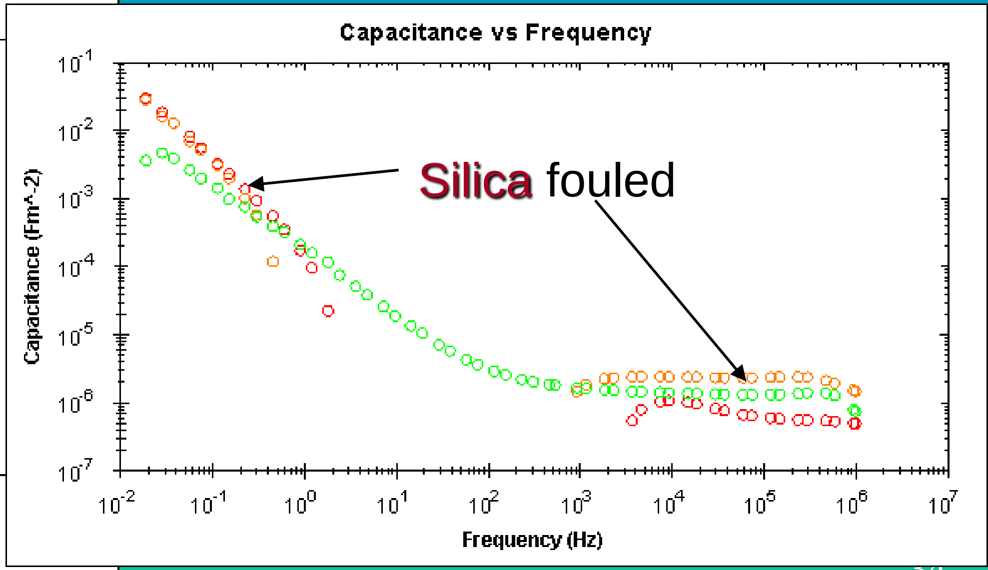
EIS Analysis of different foulants





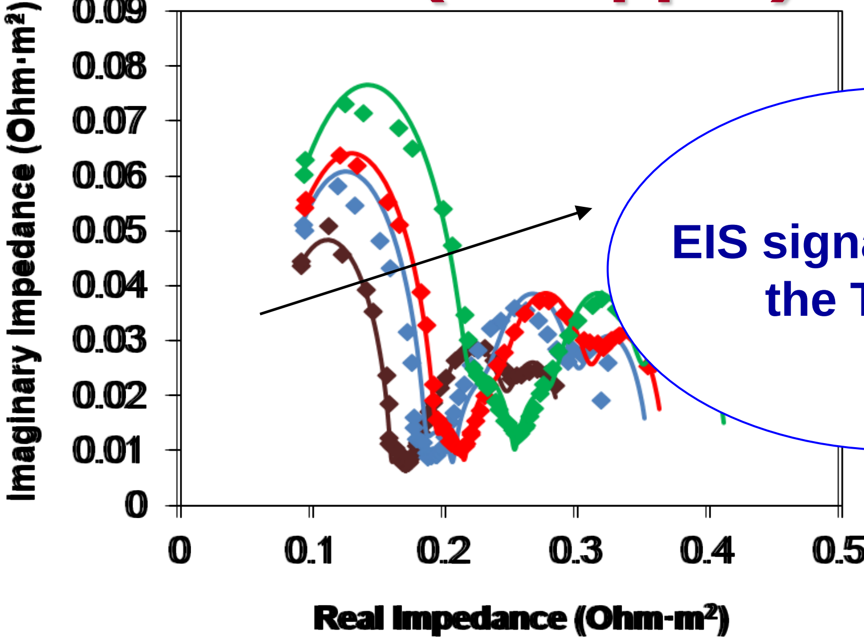
Membrane and foulant layers represented as capacitance and conductance elements. (Maxwell Wagner Elements)



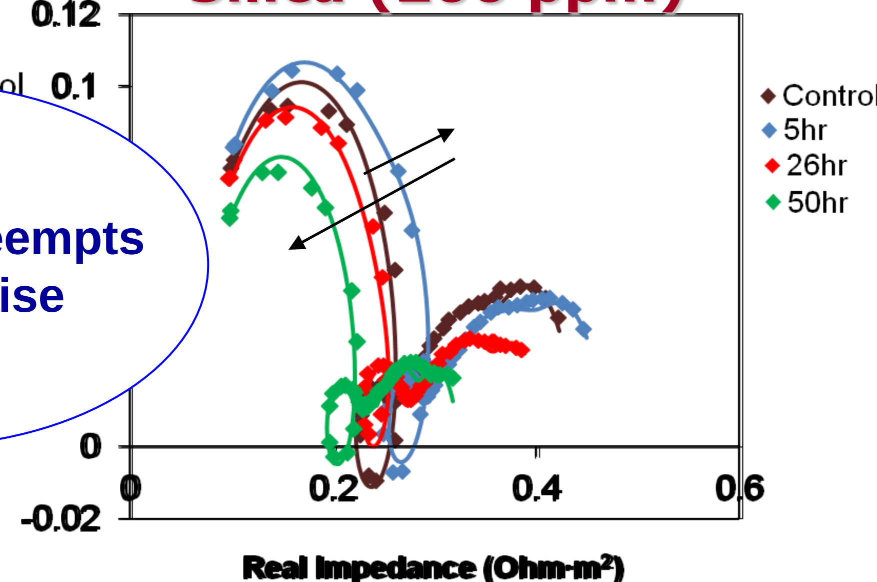


Nyquist Plots

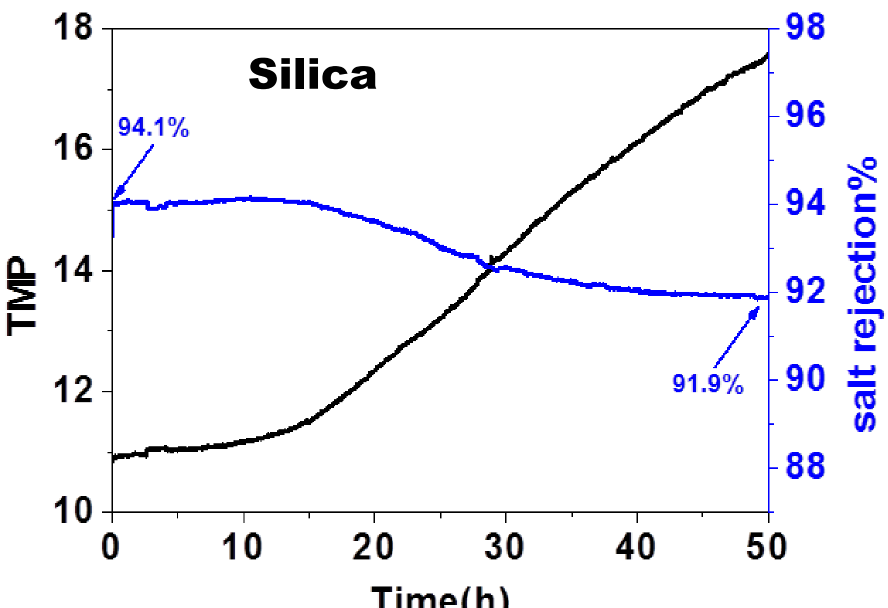
BSA (100 ppm)

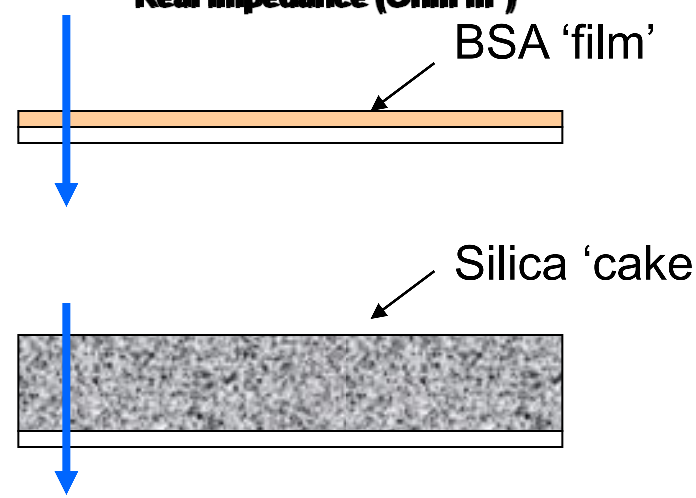


Silica (200 ppm)



EIS signal preempts the TMP rise

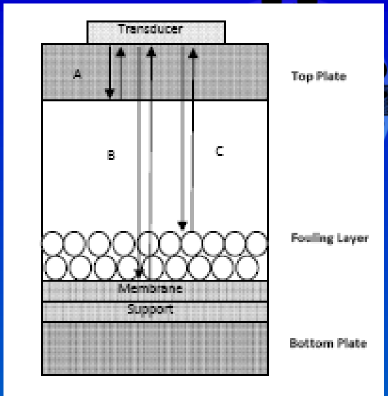




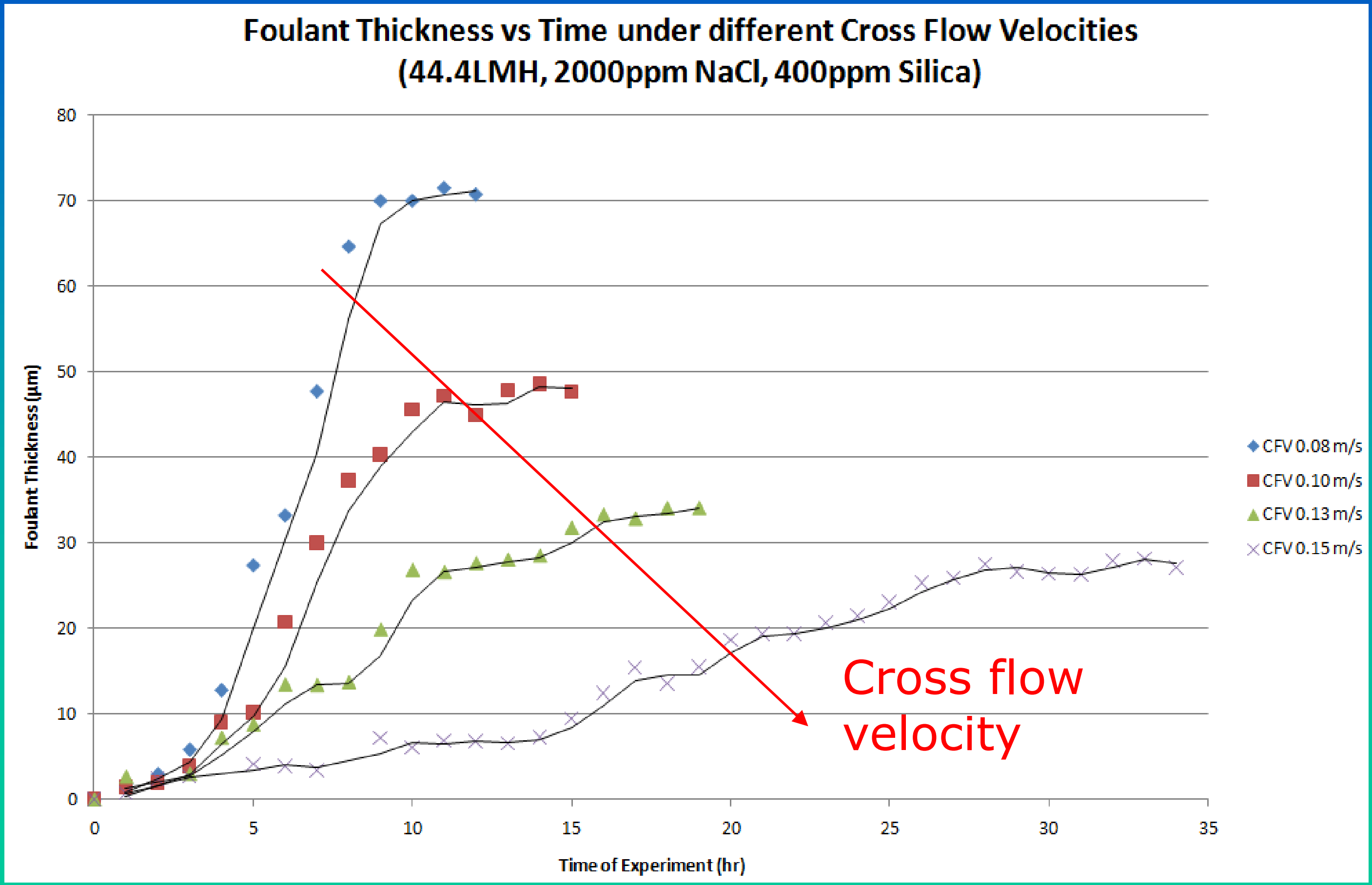
Biofilms ?

Ultrasonic Time Domain Reflectometry Fouling Monitor

- **Scale, Organics (Greenberg, Krantz et al.)**
- **Colloids (SMTC)**



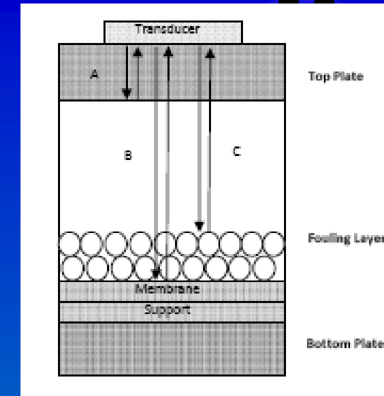
Foulant Thickness

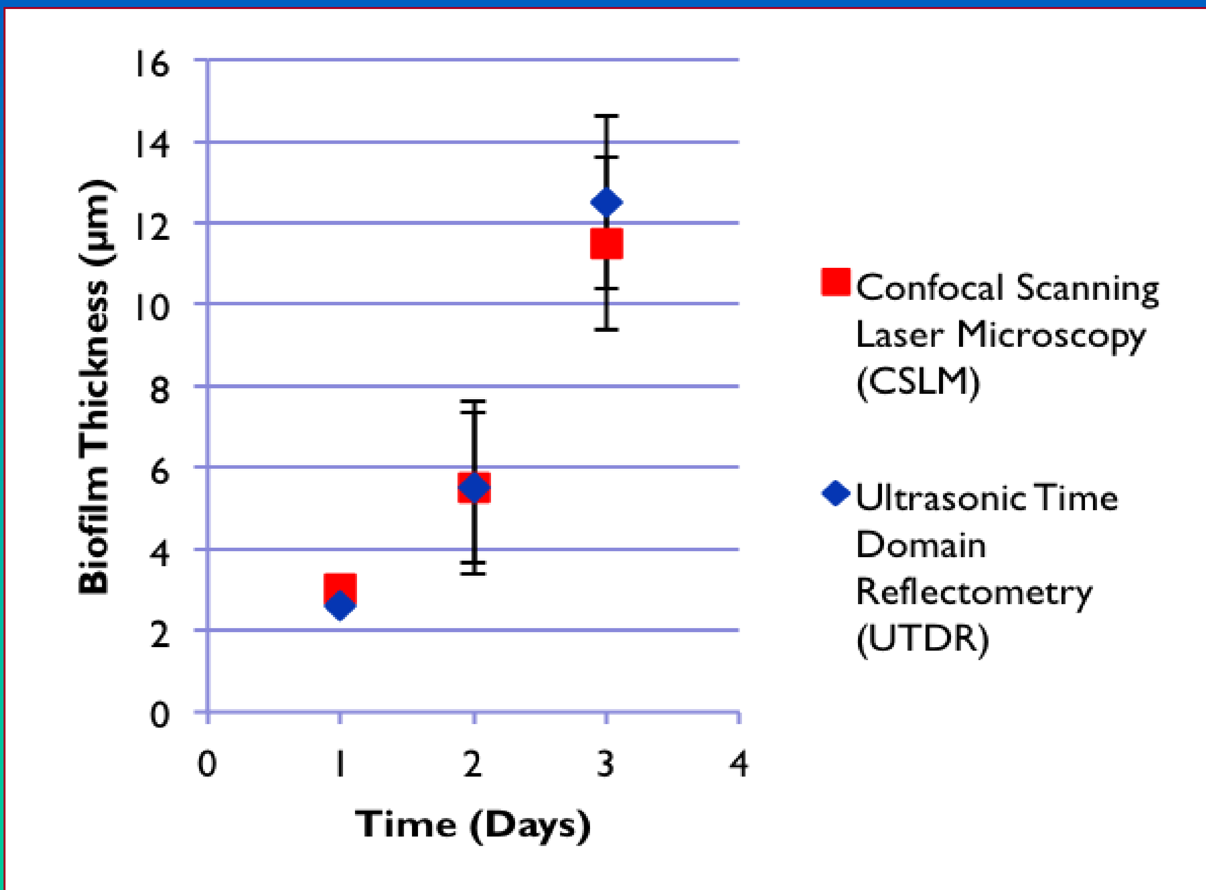


Time (hr)

Ultrasonic Time Domain Reflectometry Fouling Monitor

- Scale, Organics (Greenberg, Krantz et al.)
- Colloids, Biofilms using Acoustic Enhancer (SMTC)



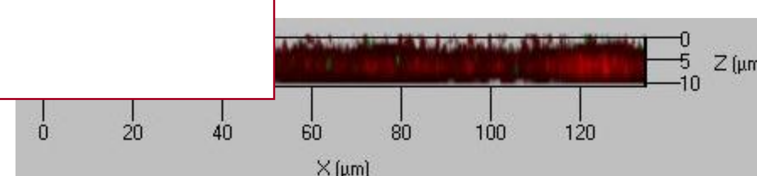


.13m/s)

TMP/TMPo

UTDR measures 8- 10 microns

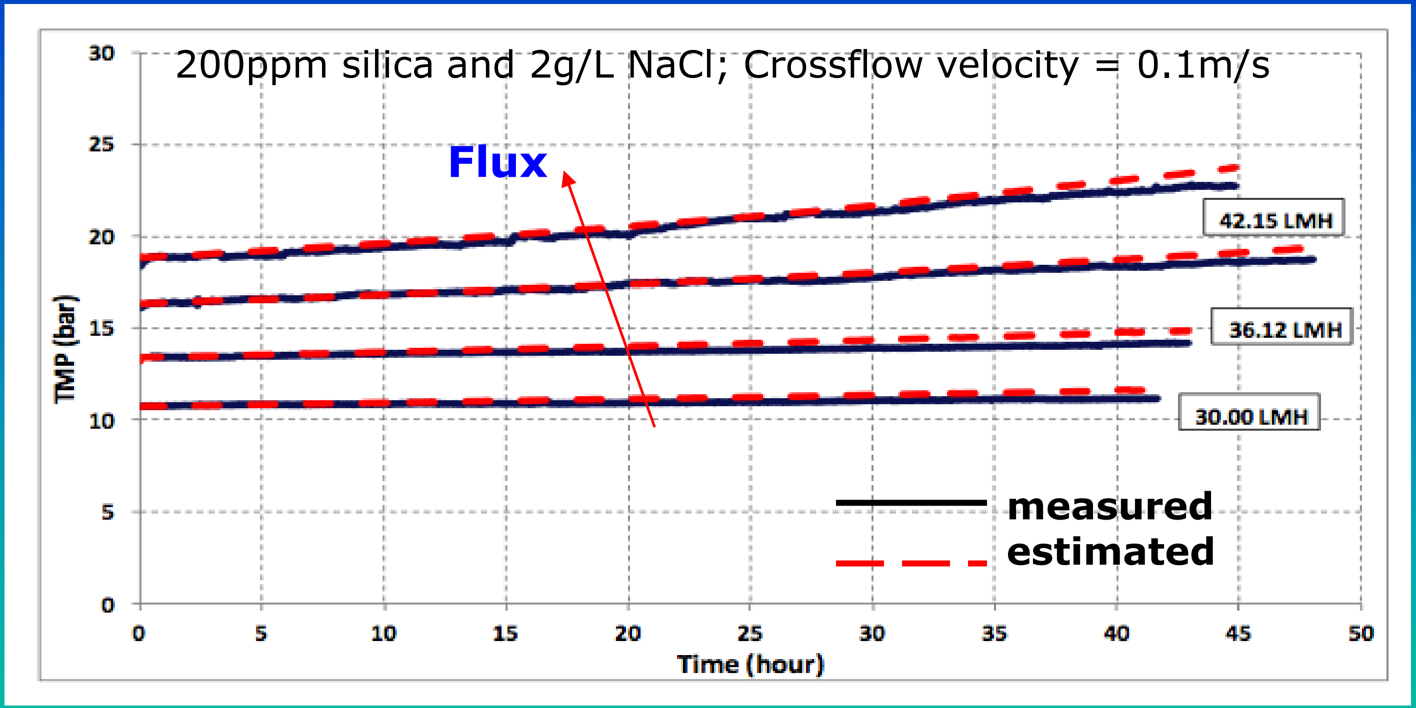
Confocal thickness of 8 -10 µm.



Sim et al. Pat. Pending

Feed Fouling Monitor & UTDR

TMP Estimation : (R_F and CEOP) Colloidal fouling



$$\Delta P = J\mu\left(R_M + R_F\right) + M\Delta\pi_{BP}$$

Feed Fouling Monitor (FFM) measures fouling propensity of feed. Estimate of R_F vs time.

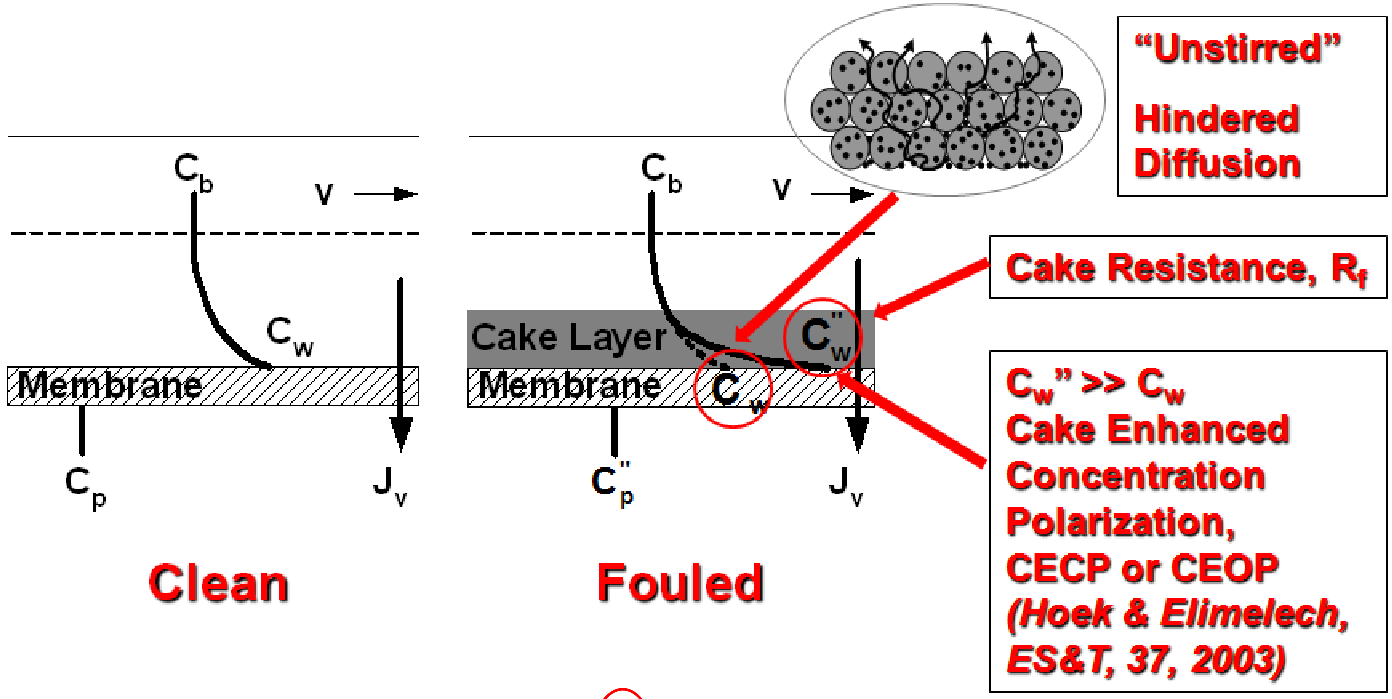
UTDR measures fouling thickness trends, to estimate CEOP

Outline

- Reverse Osmosis
  - Novel membanes/modules
  - Cascade design
  - Biofouling
- Forward Osmosis
  - Novel membranes/modules
  - PRO (osmotic power)
- Membrane Distillation
  - Novel membranes/modules
  - MDC
- Sensors & Monitoring

Biofouling in RO

- **Biofilm formation on membrane**
  - Biofilm enhanced osmotic pressure (BEOP)



$$TMP = J\mu R_m + J\mu R_f + M\Delta\Pi$$

$$M = C_w / C_b = \exp(J/k)$$

$$k_{cake} = (D\varepsilon/\tau)/\delta_{cake}$$

Biofouling in RO

- **Biofilm formation on spacer**
  - **Channel pressure drop ΔP_{ch}**

❑ **Work by Vrouwenvelder et al.**

- Biofilm preferentially form on spacer, 'blocking' flow path → increase in ΔP
- Biofouling is a spacer problem, membrane flux does not play a role
- Crossflow increases nutrient supply at the boundary layer → greater fouling
- Biofouling rate increase with crossflow through the increase in Channel Pressure Drop, $\Delta P = f(v^a)$

Exp Conditions:

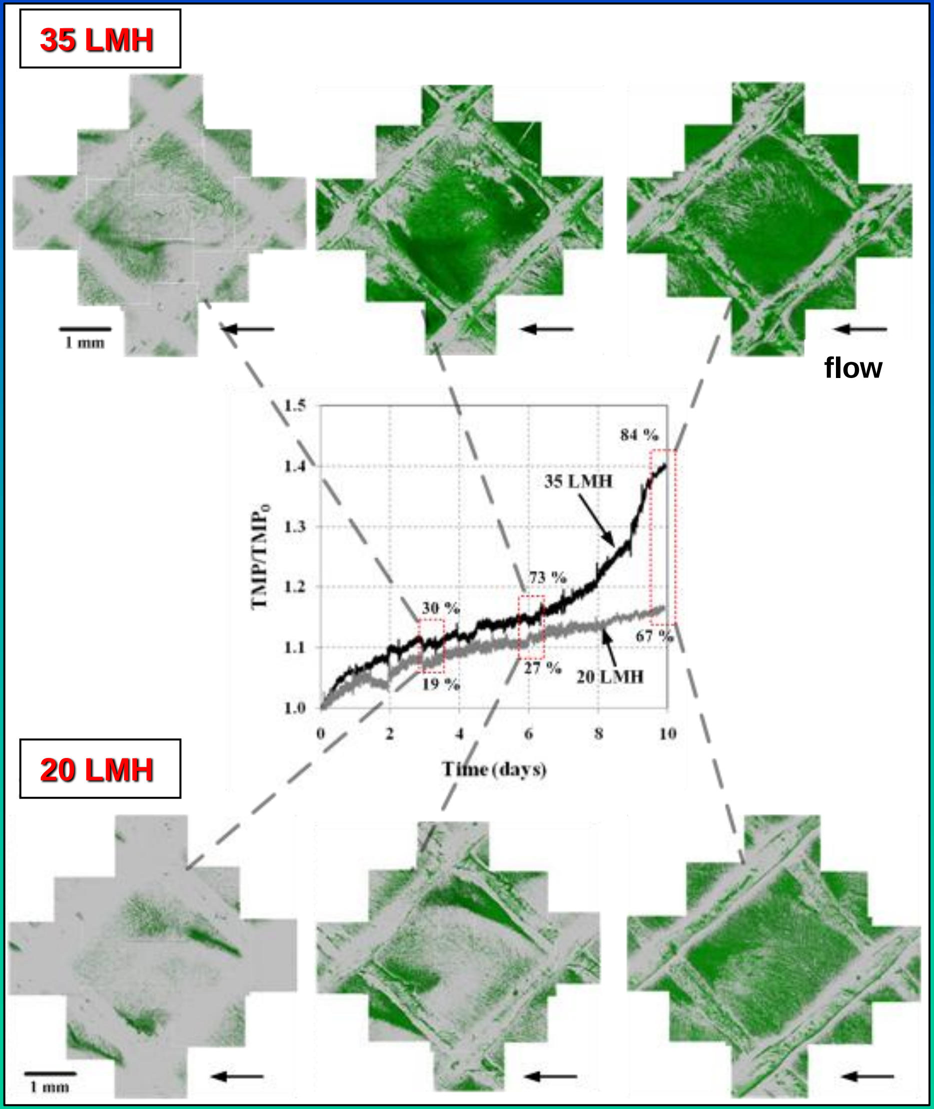
No Flux → No BEOP Effect, M = exp (J/k)

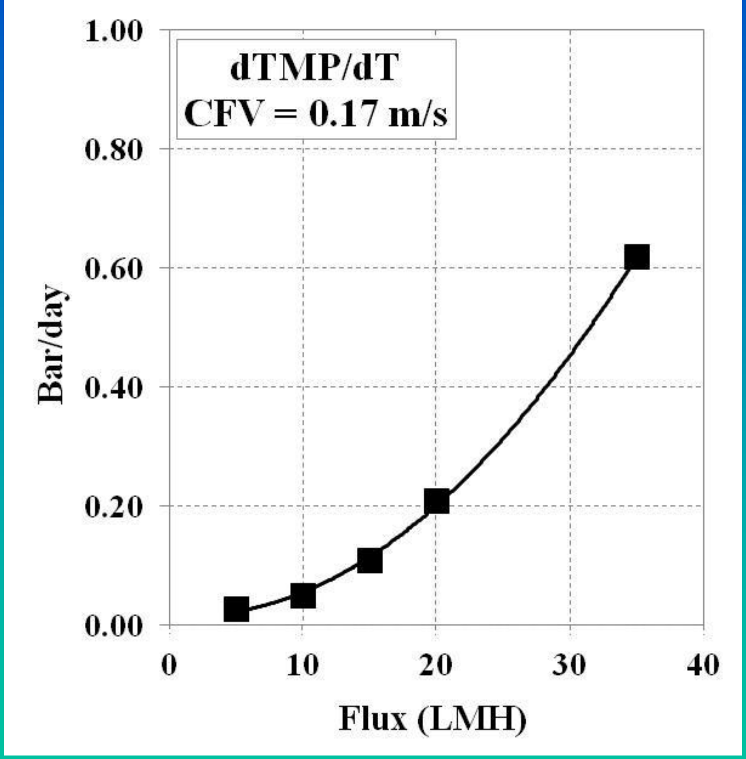
Low Salinity → Negligible BEOP Effect

Contrast to BEOP model for biofouling:
(i) flux is important (ii) crossflow decreases fouling through M = exp (J/k)

Biofouling in RO

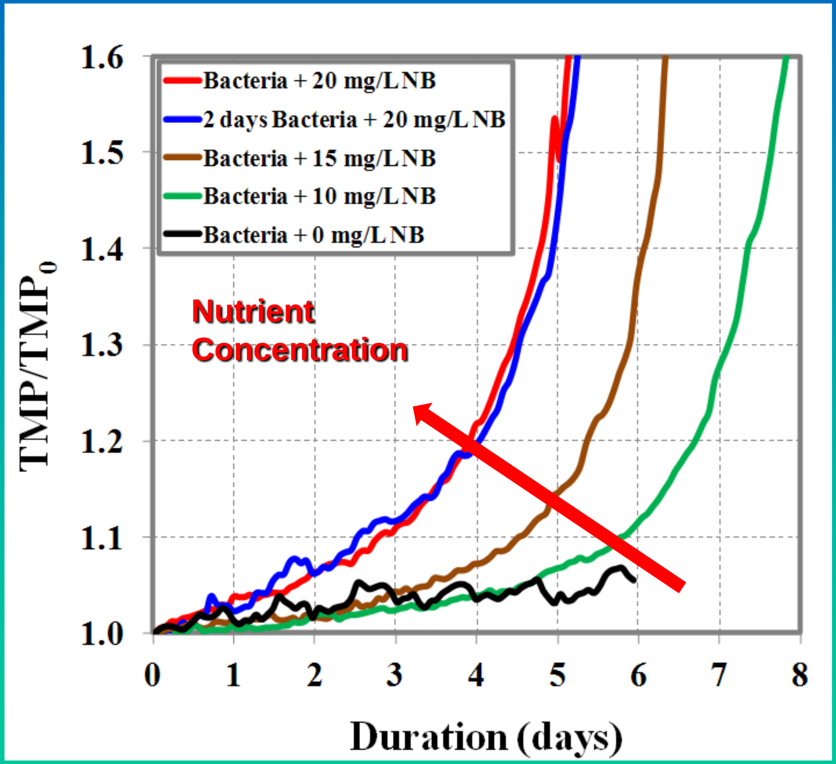
- **Effect of flux**
  - Greater fouling rate, non linear → exp (J/k)

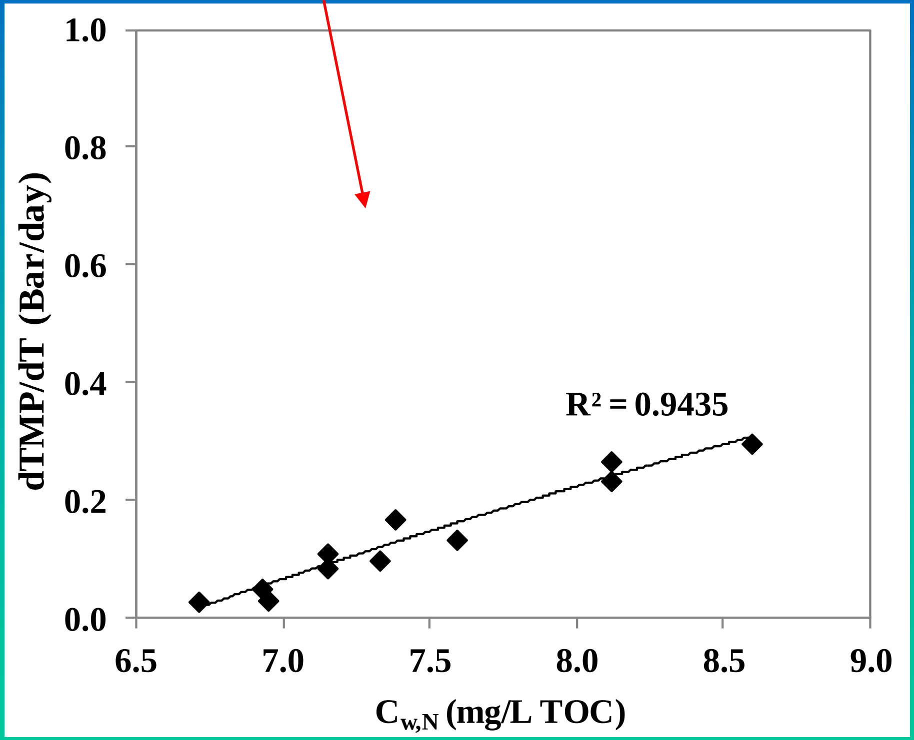




Biofouling in RO

- **Effect of nutrient**
  - Fouling rate is nutrient dependent
  - Fouling rate is a function of $M = C_w/C_b = \exp(J/k)$ → control nutrient level at membrane surface (nutrient polarization)

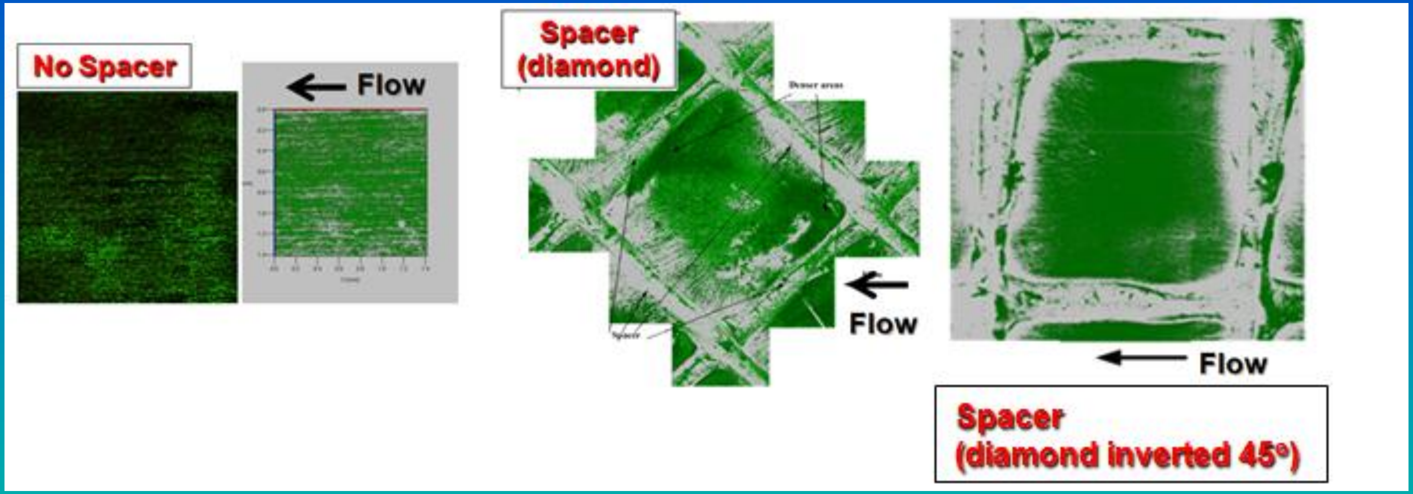


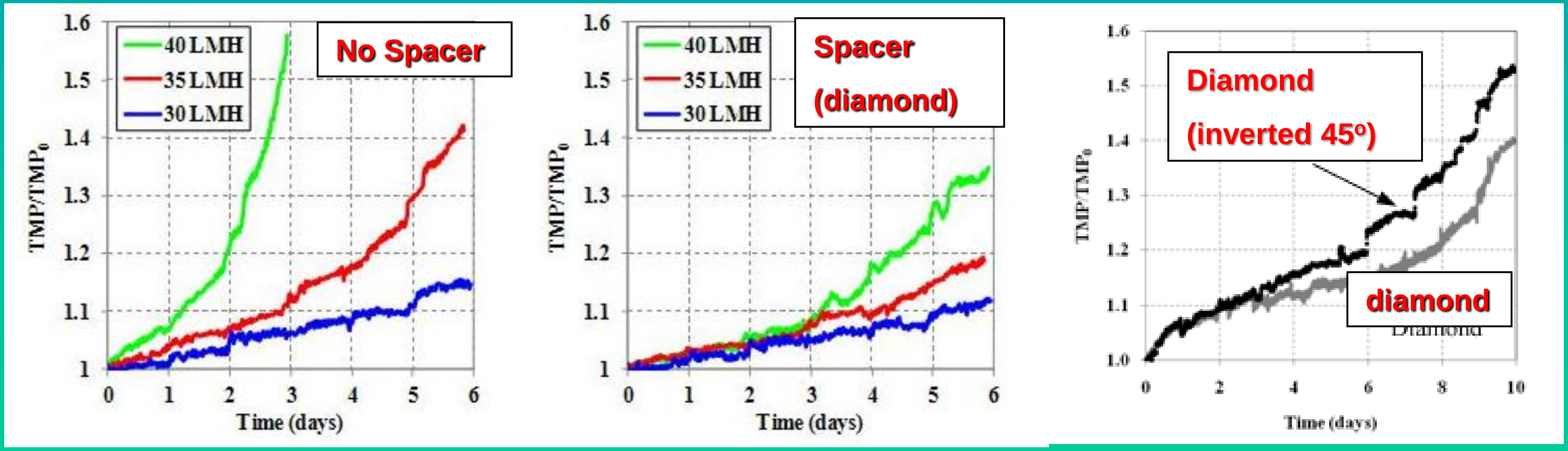


43

Biofouling in RO

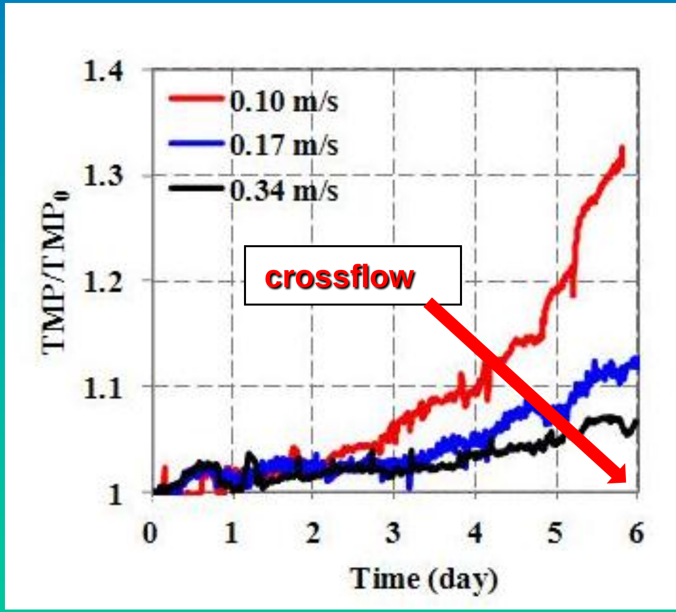
- **Role of spacer**
  - No spacer: more uniform but thicker
  - With spacer: local shear → local flux → patchy biofilm

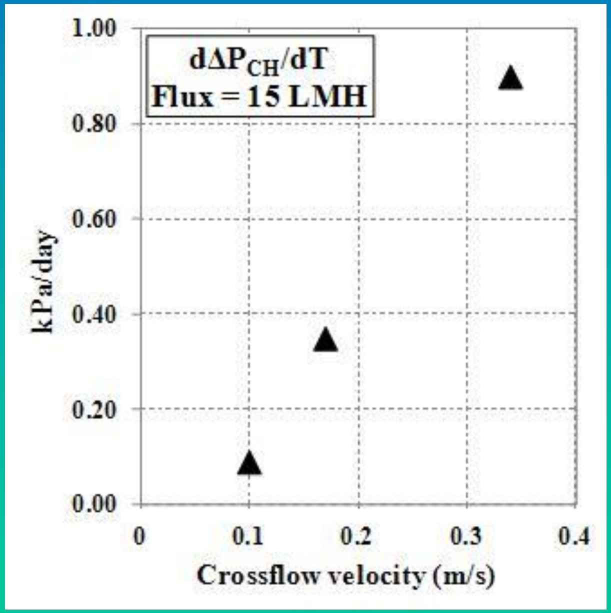


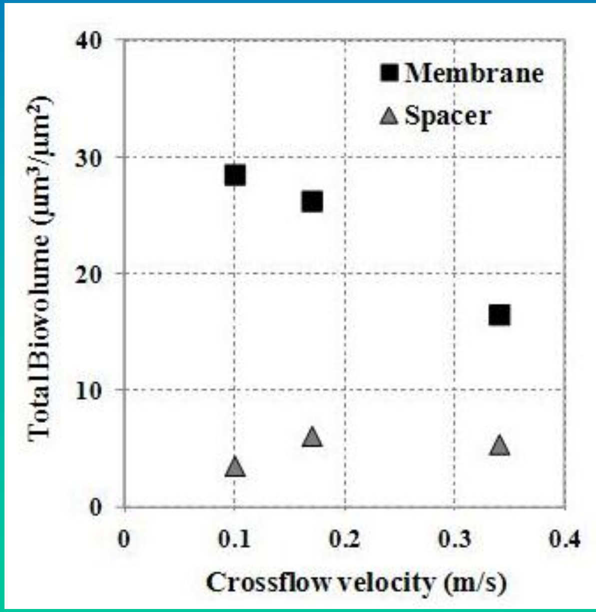


Biofouling in RO

- **Effect of crossflow**
  - Reduce fouling rate, lower *exp* (J/k) since $k \sim u^{1/3}$
  - Increase channel pressure drop, $\Delta P_{ch} \sim u^2$
  - Membrane (flux & crossflow is important) vs. spacer (only crossflow is important) problem
    - $dTMP/dt >> d\Delta P_{ch}/dt$







45

Biofouling in RO

- **Control strategies**
  - Even flux – internal hybridization

  - Crossflow – lower exp (*J/k*)
  - Nutrient removal, far more effective than control "number" of bacteria
  - Spacer design

ACKNOWLEDGEMENTS

EDB Singapore and Environment and Water Industry Programme Office (EWI) under National Research Foundation (NRF) for supporting the Singapore Membrane Technology Centre.

http://smtc.ntu.edu.sg

SMTC website: http://smtc.ntu.edu.sg

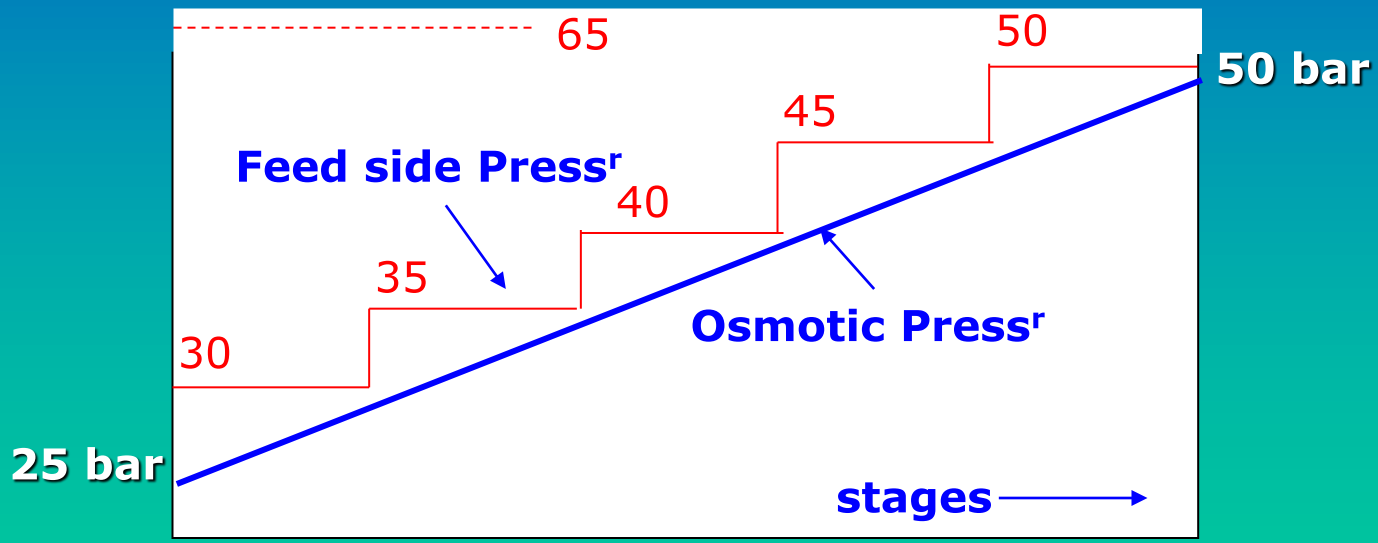
Thank You

Supplementary Information

Reverse Osmosis

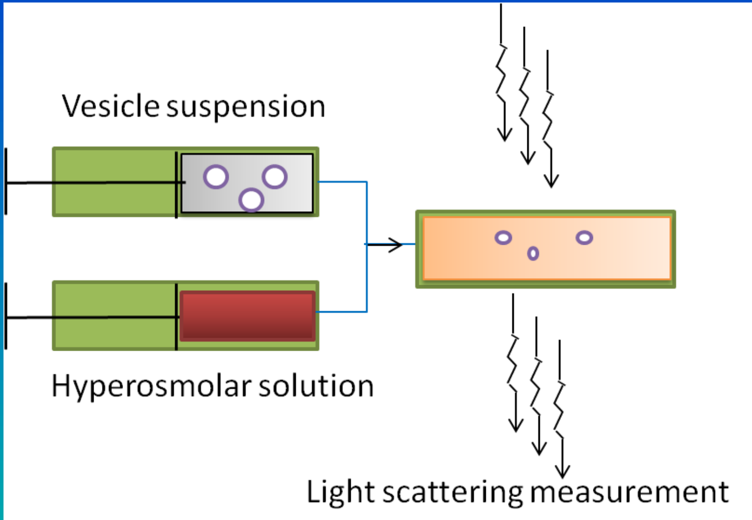
Energy usage is ~ 2 x the theoretical minimum

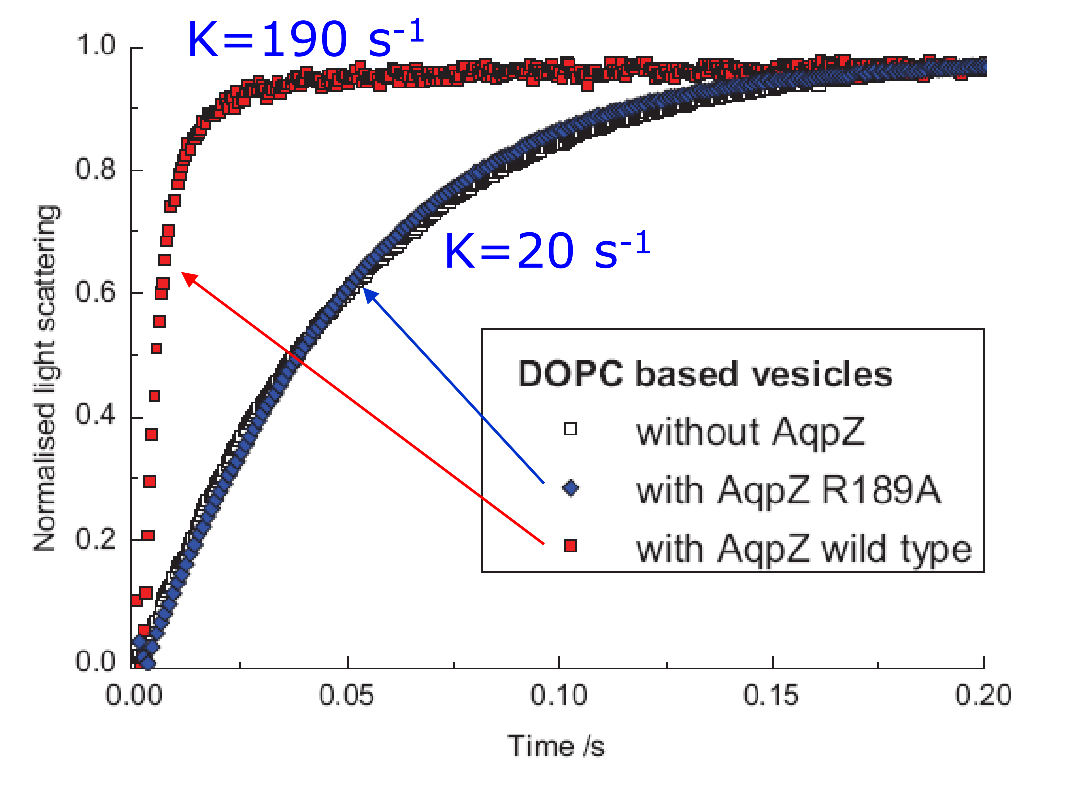
'Super flux' membranes could save ~30% desalination energy.



'Close to Osmotic Pressure Strategy'

Aquaporin Characterization

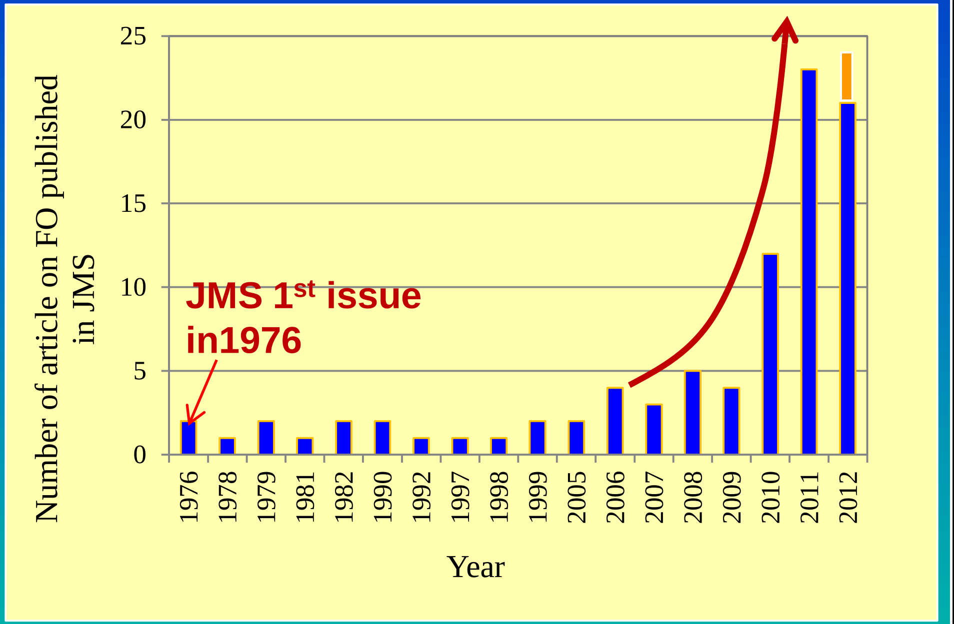




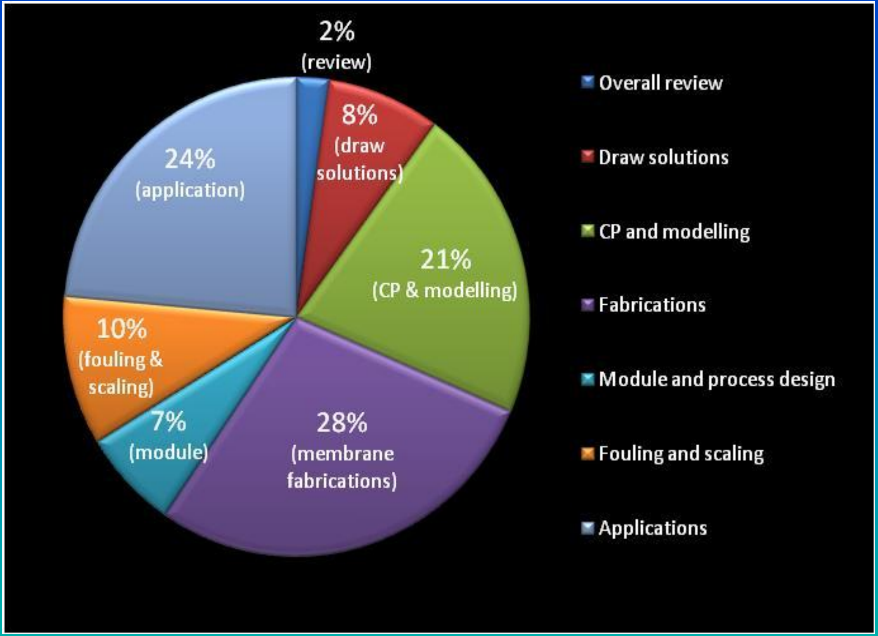
Stopped-flow measurement of water permeability

Aquaporin Z wild type permeability ~ 10x that of Aqp Z R189 mutant

Resurgence of Interest in Various Osmotic Processes



Publications of FO papers in JMS up to June 2012



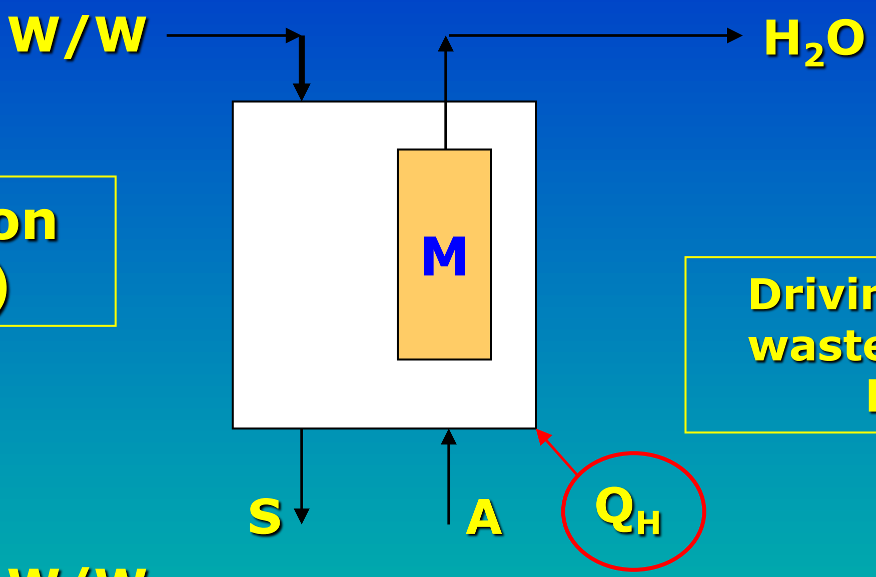
Distribution of FO publications in each section

Journal of Membrane Science*: Virtual Special Issue*
Forward Osmosis: Current Status and Perspectives
Editors: Rong Wang, Laurentia Setiawan, Anthony G. Fane

High Retention MBRs

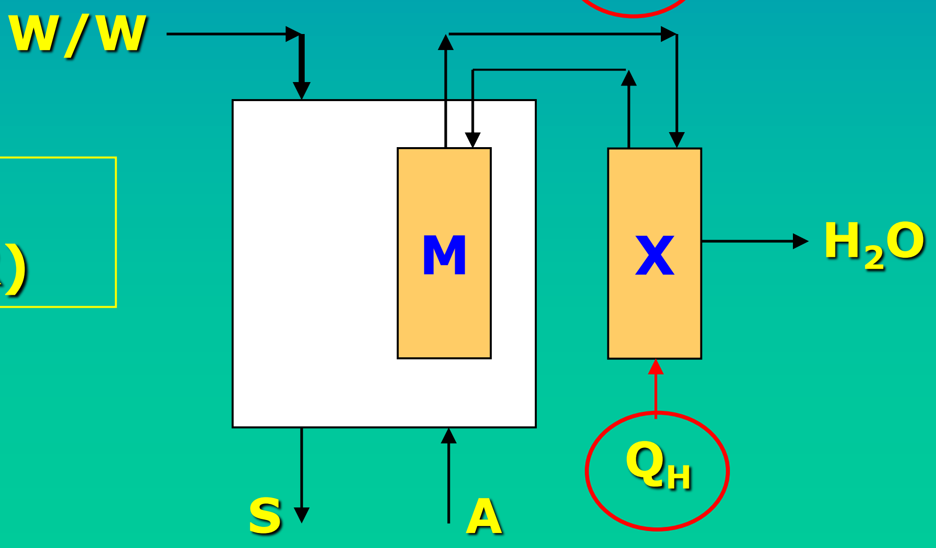
(ORT ≠ HRT , to improve permeate quality)

Membrane Distillation Bioreactor (MDBR)



Driving force : waste or solar heat

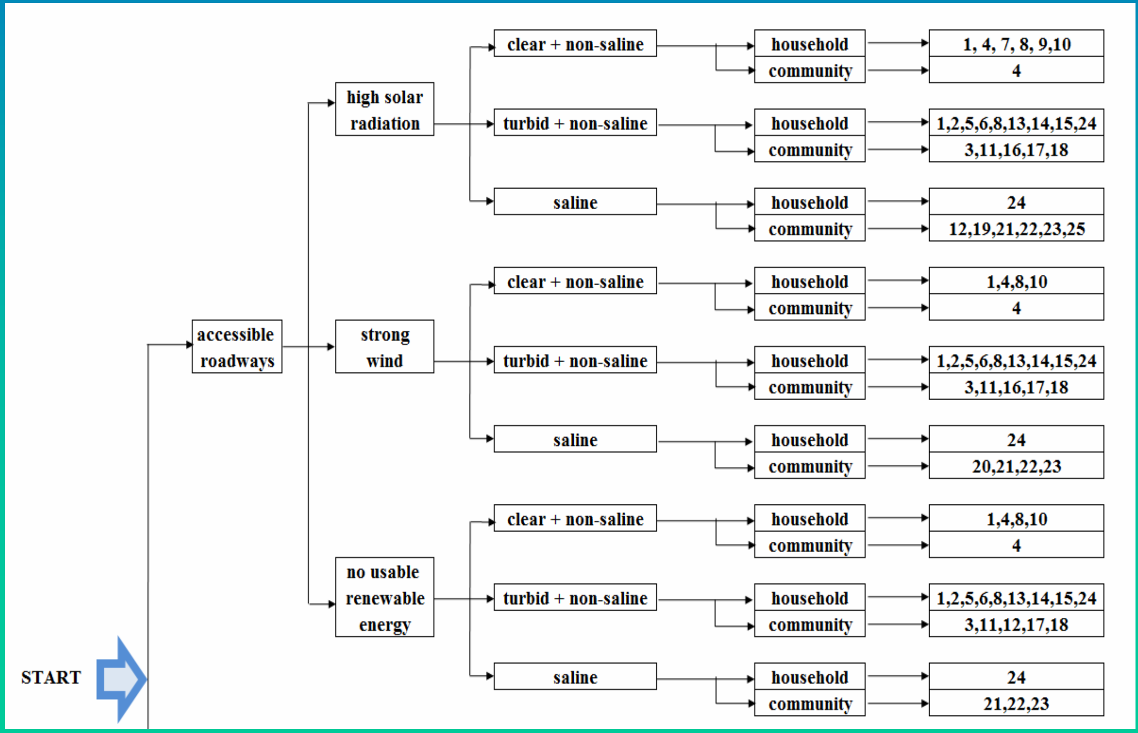
Forward Osmosis Bioreactor (FOMBR)



Membranes for Special Needs

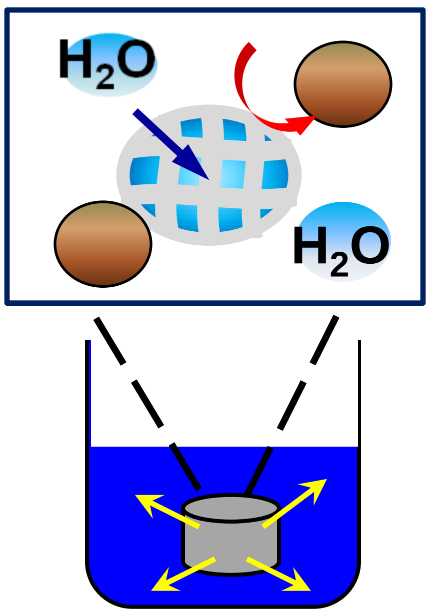
Applications in Myanma & Indonesia (Adrian Yeo et al.)

Decision tree for process selection
(Loo et al. Water Res, 46 (2012))

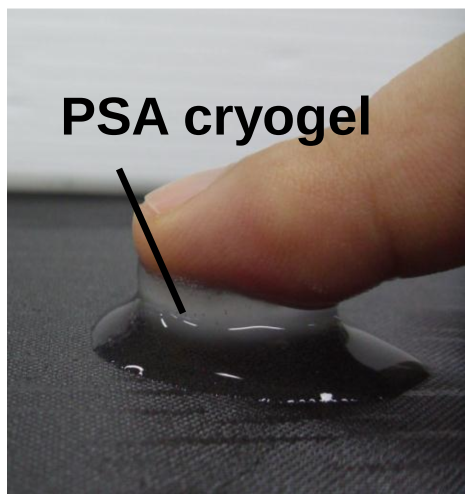


Cryogels as integral membranes for emergency water treatment

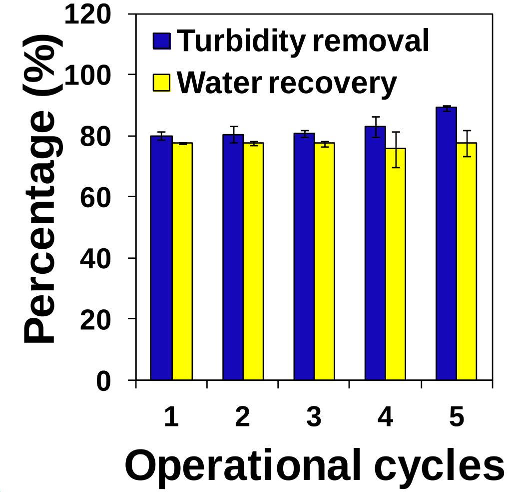
(a) Dried/deswollen PSA cryogel

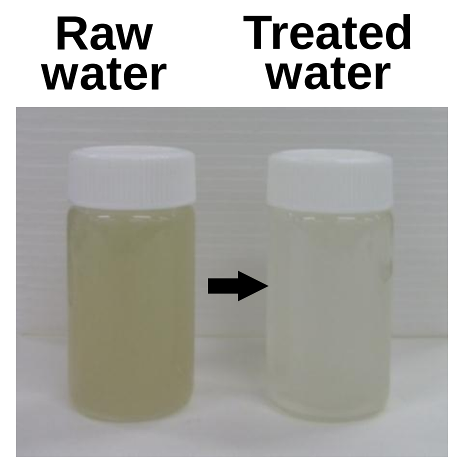


(b) Swelling in contaminated water



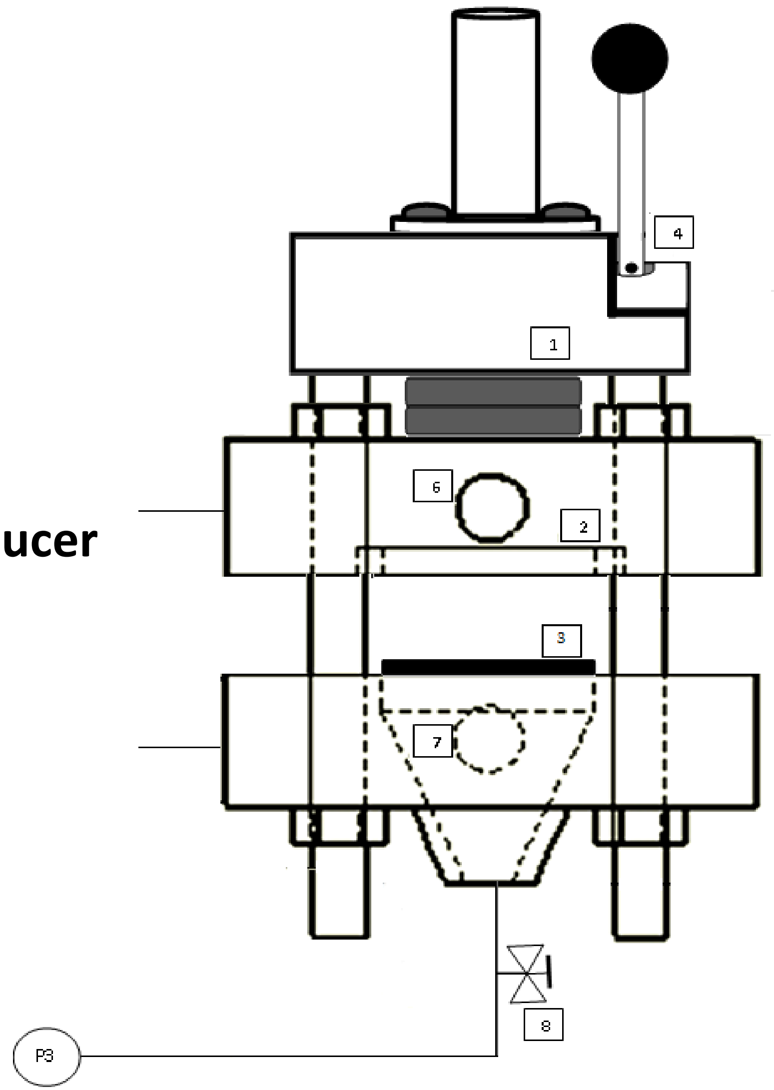
(c) Water recovery by manual compression





Loo et al., Soft Matter, 9 (2013))

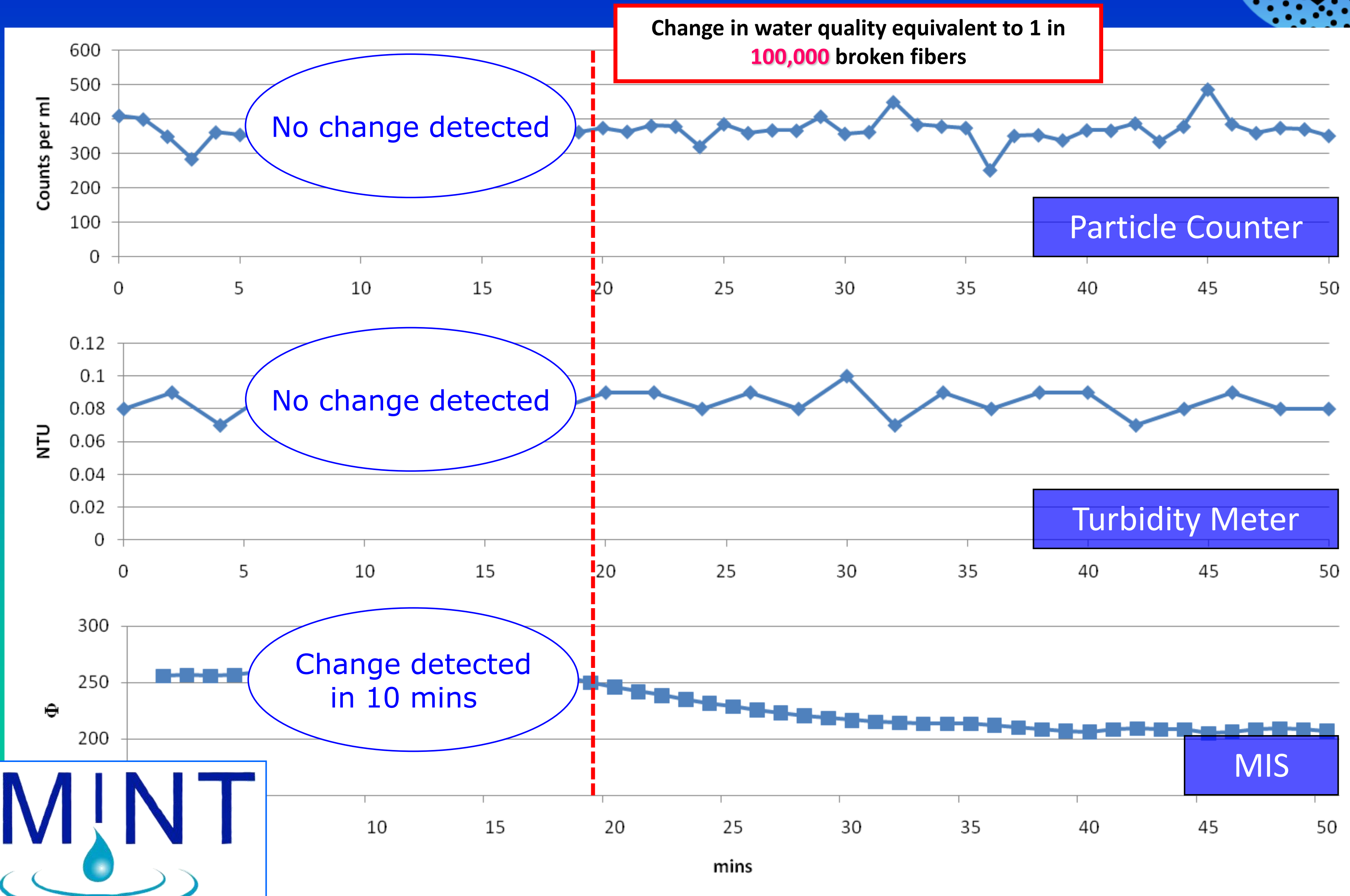
Membrane Integrity Sensor (MIS)



Label:

1 Spring
2 O-Ring
3 Membrane
4 Lever
5 Pressure Transducer
6 Feed (Inlet)
7 Backwash
8Tuning Valve

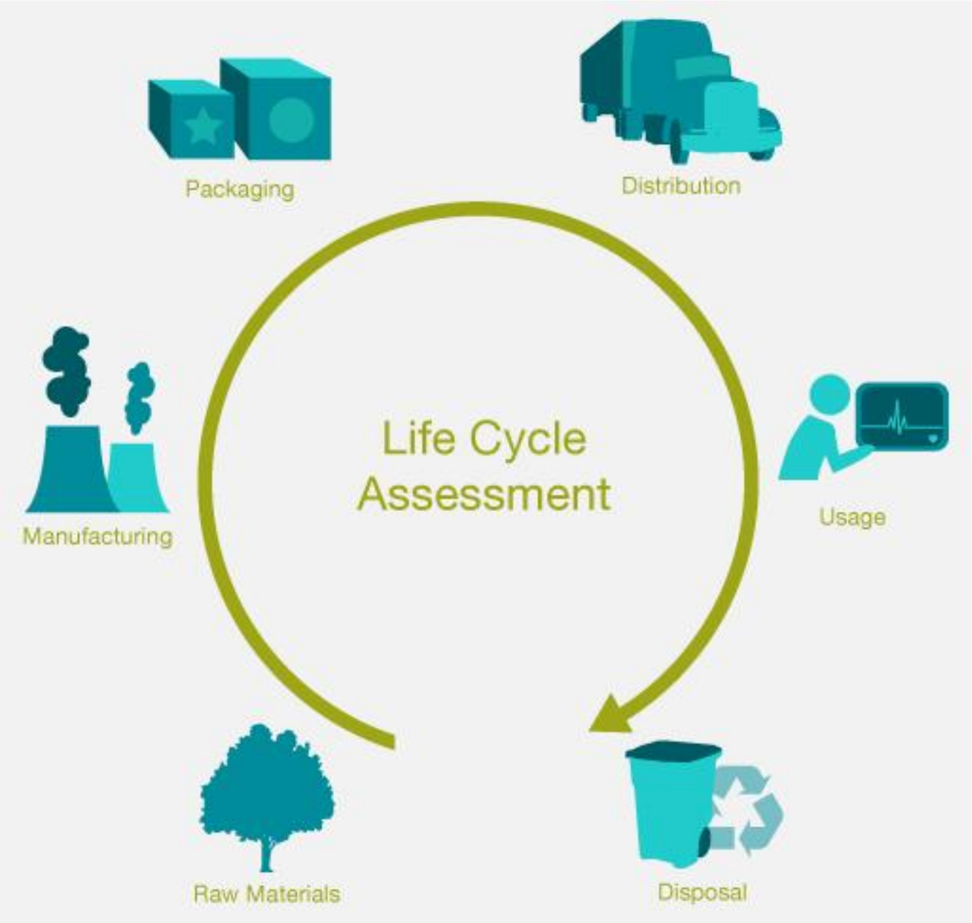
0.001% compromised (1 in 10^5 fibres)



Life Cycle Assessment (LCA)

Member of the NEWRI Ecosystem

LCA is a technique to assess environmental impacts associated with all the stages of a product's life from-cradle-to-grave.



Advantages:

(1) Holistic evaluation
upstream + usage + downstream

(2) Wide application
industry + government

(2) Top research area
publications + special issue

LCA research in SMTC NTU

Member of the NEWRI Ecosystem

<u>LCA fundamental study:</u> Singapore life cycle Inventories [1], Customization of system boundary & impact indicators to local context [2, 4]; Improvement of impact assessment models for brine disposal [3]

<u>LCA applications:</u> Desalination [1], Wastewater management [5]; Disinfection process [6], Water supply plans [under development]; Innovative membrane technologies [under development]

<u>LCA for decision making:</u> Integration with economic & social impact analysis [4], normalization and weighting system for Singapore [under development]

1) *Jin Zhou, Victor W.C. Chang, Anthony G. Fane (2011a). "Environmental LCA of Brackish Water Reverse Osmosis Desalination for Different Electricity Production Models", Energy and Environmental Science, Vol. 4, No. 6, pp. 2267-2278.*
2) *Jin Zhou, Victor W.C. Chang, Anthony G. Fane (2011b). "Environmental LCA of RO Desalination: The Influence of Different LCIA on the Characterization Results", Desalination, Vol. 283, pp. 227-236.*
3) *Jin Zhou, Victor W.C. Chang, Anthony G. Fane (2013). "An Improved LCIA Approach for Assessing Aquatic Eco-toxic Impact of Brine Disposal from Seawater Desalination Plants", Desalination, Vol. 308, pp. 233-241.*
4) *Jin Zhou, Victor W.C. Chang, Anthony G. Fane (2013). "Issues of Applying LCA to Desalination: Feasibility, Reliability, and the Potential to Use LCA for Decision Making", submitted to Water Research*
5) *Bernard J.H. Ng, Jin Zhou, Victor W.C. Chang, et.al. (2013). "Environmental Life Cycle Assessment of Municipal Wastewater Streams in Conventional Activated Sludge System", submitted to International Journal of Life Cycle Assessment.*

Water for All
Conserve, Value, Enjoy
PUB

Desalination in Singapore – Current Status & A Peek into the Future

Puah Aik Num
Technology Department
PUB Singapore

PUB : Part of Singapore's MEWR Family

Ministry of the Environment and Water Resources

To deliver and sustain a clean and healthy environment and water resources for all in Singapore.

National Environment Agency

To ensure a sustainable quality environment in Singapore

- *Clean Land*
- *Clean Air*
- *Public Health*

PUB

Water for All: Conserve, Value, Enjoy

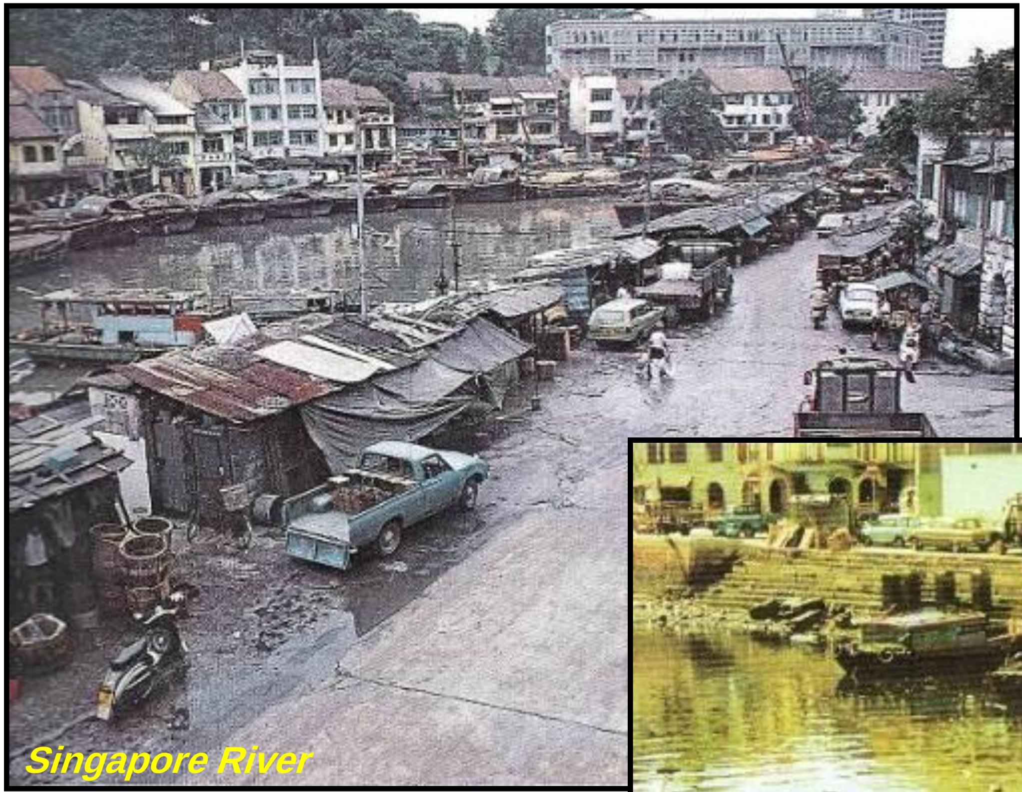
To ensure an efficient, adequate and sustainable supply of water

- *Water Supply*
- *Used Water*
- *Drainage*

SINGAPORE WATER SCENES THEN AND NOW

What we were like in the Sixties

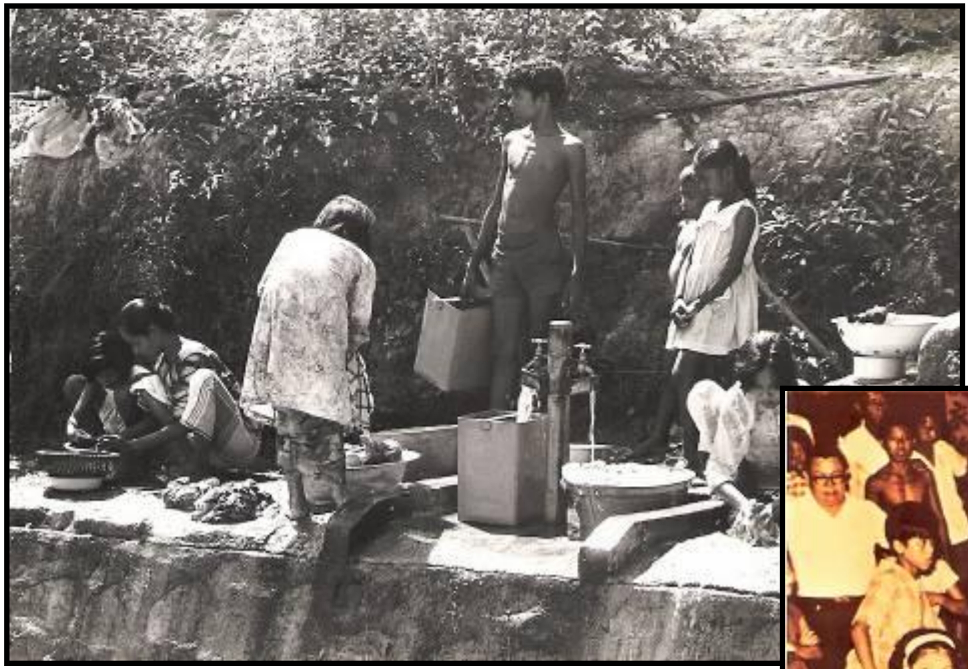
40 years ago…



Singapore River

Singapore River

1960's



Water resources were scarce…

Last water rationing in 1963

1960's

Public Health Concerns

- *Proper sanitary facilities were lacking…*
- *Public Health Conditions were poor…*

1960's

Our rivers were polluted…

80's and 90's

Clean Rivers

Pristine reservoirs…

Before 1960's: Reservoirs in Protected Catchments

1970's: Estuarine Reservoirs

1980's: Reservoirs in Urbanised Catchments

Singapore today…

PUNGGOL TOWN
A Waterfront Eco-Town for the Tropics

SINGAPORE WATER CHALLENGES

Singapore’s Water Challenges

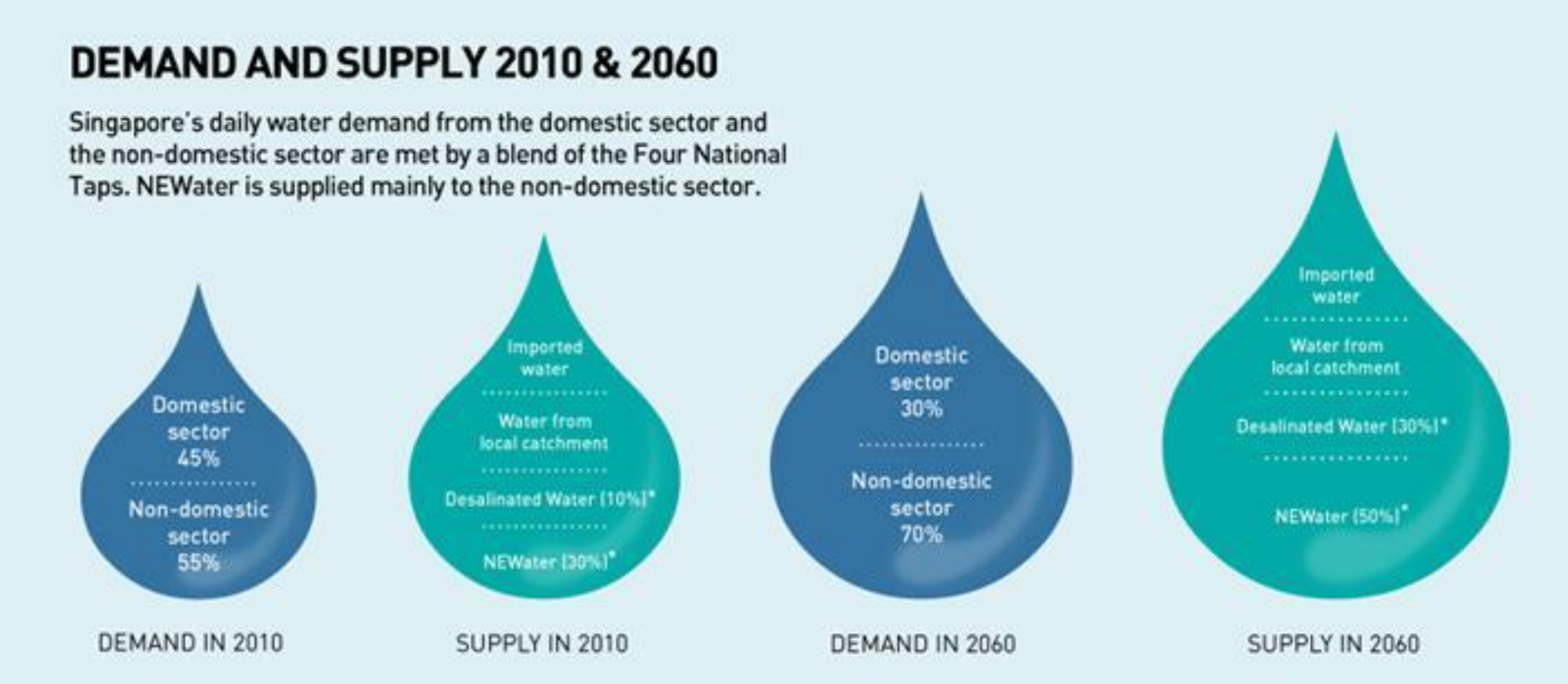
- **Land Area: 710 km^2**
- **Population: 5.18 million people**
- **Water Demand: 1.8 million m^3/day**

- **Rainfall: 2.4 m/year** ➔ *Lack of Storage*
- **Catchment areas: 66%** ➔ *Competing Land Use*

Challenges Ahead

Rising Energy Prices

Stringent Regulations & Public Expectations

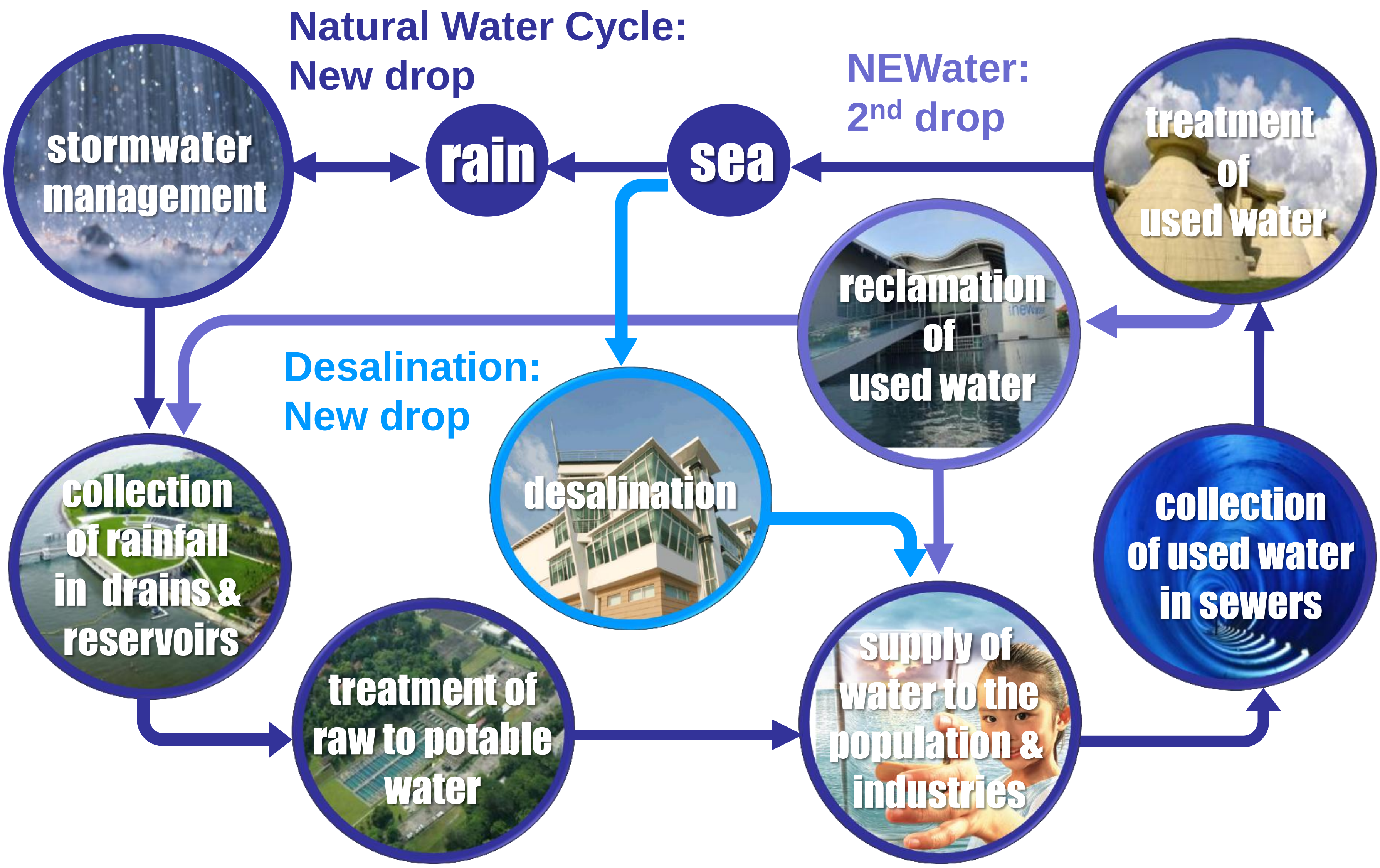


2012 water demand = 1.8 million m^3/day

2060 water demand = **almost double that of today**

INTEGRATED WATER MANAGEMENT

Closing the Water Loop




FOUR NATIONAL TAPS
Desalinated water
NEWater
Imported water
(from Johor)
Water from
local catchment

LEVERAGING ON TECHNOLOGY

Leveraging Technological Innovations

R&D to achieve water sustainability

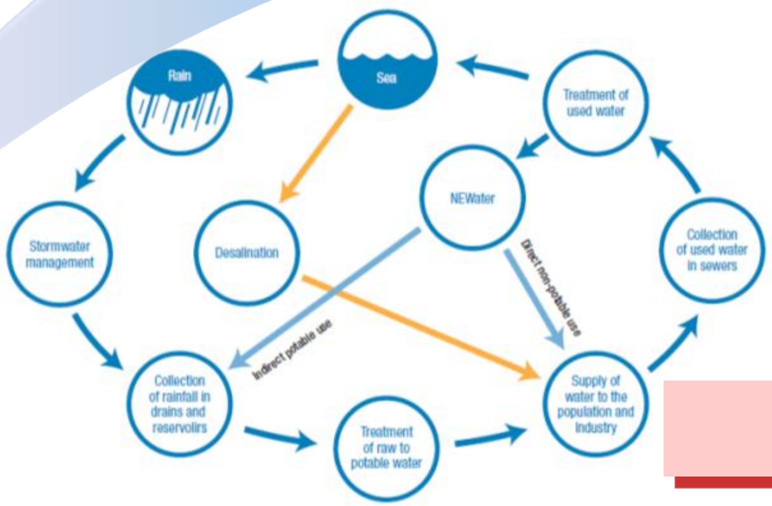
Objectives

Reduce Production and Distribution Cost

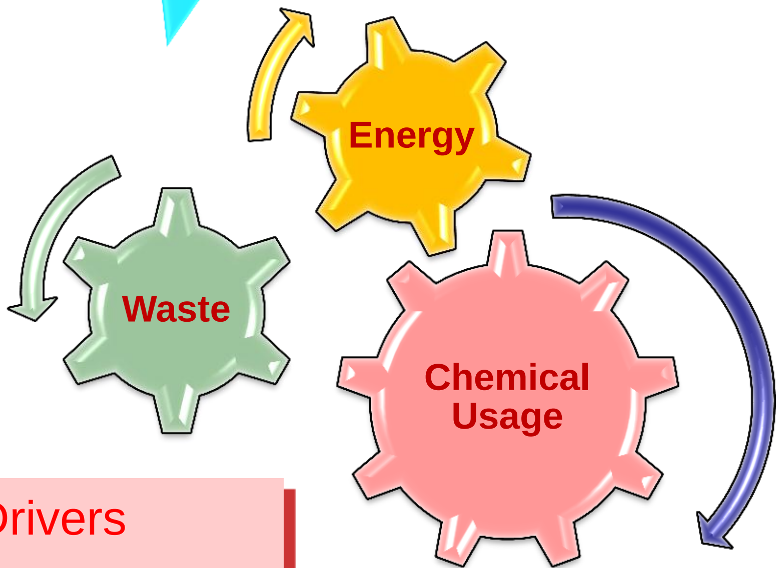
Enhance Water Quality and Security

Increase Water Resources

Water for All: Conserve, Value, Enjoy



Drivers



"Water for All" - PUB's Investment in R&D Innovation

PUB started its R&D programme in 2002.

- No. of Projects to-date: 338
- Annual R&D Budget:
    - S$5 mil from 2004 to 2009
    - Increased to S$20 mil in 2010
- Total Project Value: S$191 mil
- Average annual R&D investment: S$17.4 mil

PUB's Role in R&D

PUB
Water for All: Conserve, Value, Enjoy

Technology & Water Quality Office

PDIKM Teams

- Water Supply Plants
- Water Supply Network
- Water Reclamation Plants
- Water Reclamation Network
- Catchment & Waterways
- InfoComm

Demonstration -plant studies

Pilot-plant studies

Breakthroughs

Upstream fundamental research*

NUS National University of Singapore

Nanyang Technological University

AWT Centre for Advanced Water Technology

Agency for Science, Technology and Research SINGAPORE

Ngee Ann Polytechnic

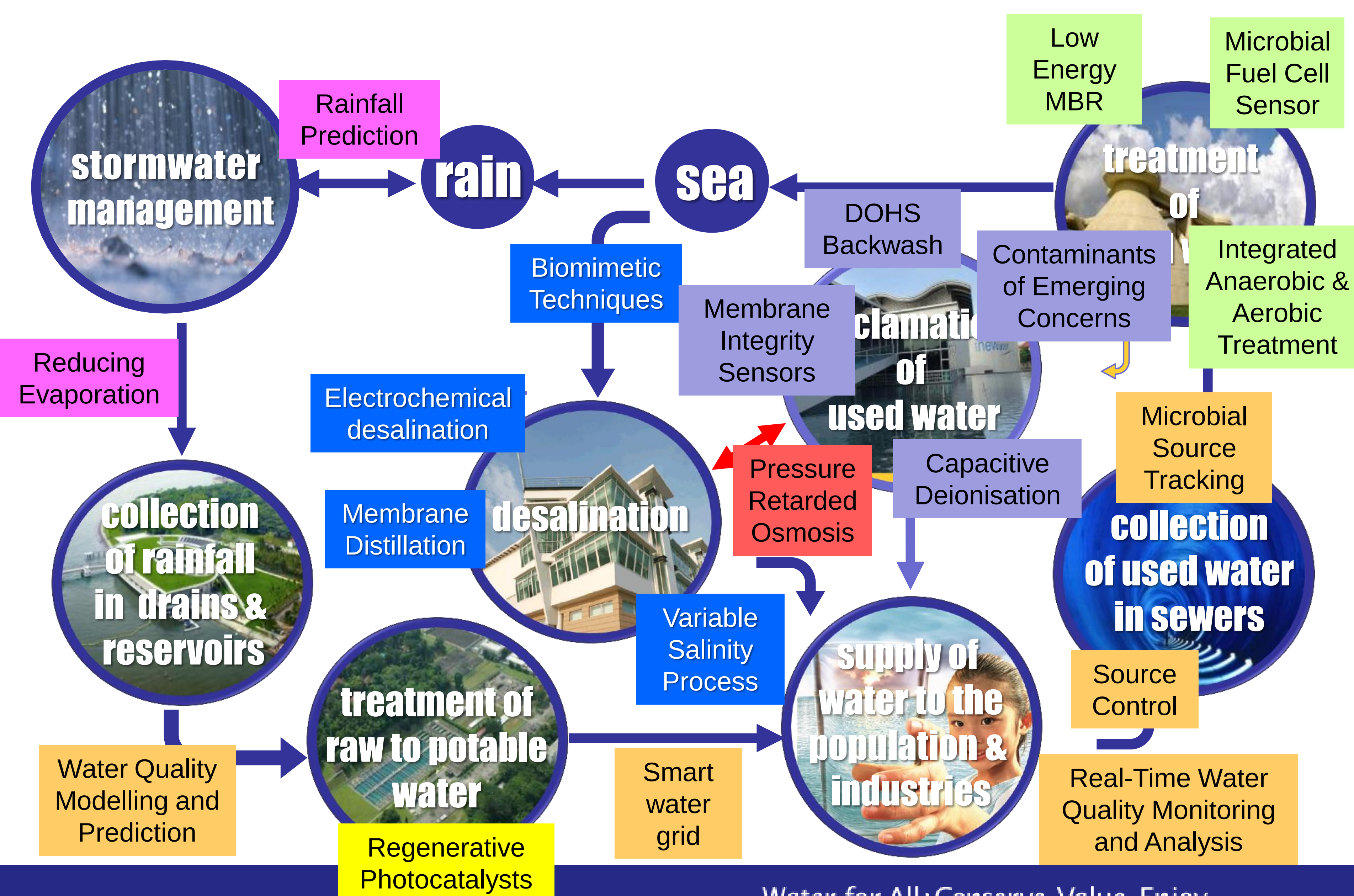
iESE

Tropical Marine Science Institute

NEWRI

** Usually carried out in laboratory scale in tertiary and research institutes*

R&D Projects across the Water Loop



Revised Technology Roadmap

Technically Feasible and Economically Viable Water Solutions

New Ideas and Innovations

Increase Water Resources

Improve and Protect Water Quality

Decrease Water Production Costs

Lower Chemical Usage

Reduce Energy Consumption

Minimize Waste Generation

Biological Processes
- UASB-MBR
- Anaerobic / Anammox Systems
- Biogas production
- Energy recovery systems

Chemical Redox
- Advanced oxidation technologies
- Disinfection technologies

Water Distribution
- WQ sensor development
- Smart grid development (data mining and data analytics)
- Network Modelling / Cloud computing

Watershed Management and Flood Management
- WQ sensor development
- Intelligent watershed management (data mining and analytics)
- Climate change modelling
- Phytoremediative treatment of water

Membranes for Desal & NW
- Ceramic Membranes
- Electrochemical desalting
- Biomimetics / Biomimicry
- Membrane fouling control
- Process improvements
- Membrane improvements

Sludge and Brine Management (EWW Nexus)
- Osmotic power PRO/RED
- Sludge-to-energy conversion
- Resource recovery from residues
- Sludge management

Sensors and Instrumentation
- Rapid detection of emerging pollutants, PPCPs, nanoparticles
- Fish biosensors
- Rapid microbial detection
- Sensors for membrane systems

Groundwater / Underground Caverns
- Geophysical/geotechnical surveys
- Water quality management/treatment
- Sustainable water extraction and use

Decentralised Water Treatment Technologies
- Small-scale point of use technologies
- Greywater Recycling
- Stormwater technologies

Industrial Water Technologies
- Industrial wastewater treatment
- Membrane distillation
- Seawater cooling
- Adsorption chillers
- Novel heat exchangers
- Reduction in evaporative loss

Desalination in Singapore

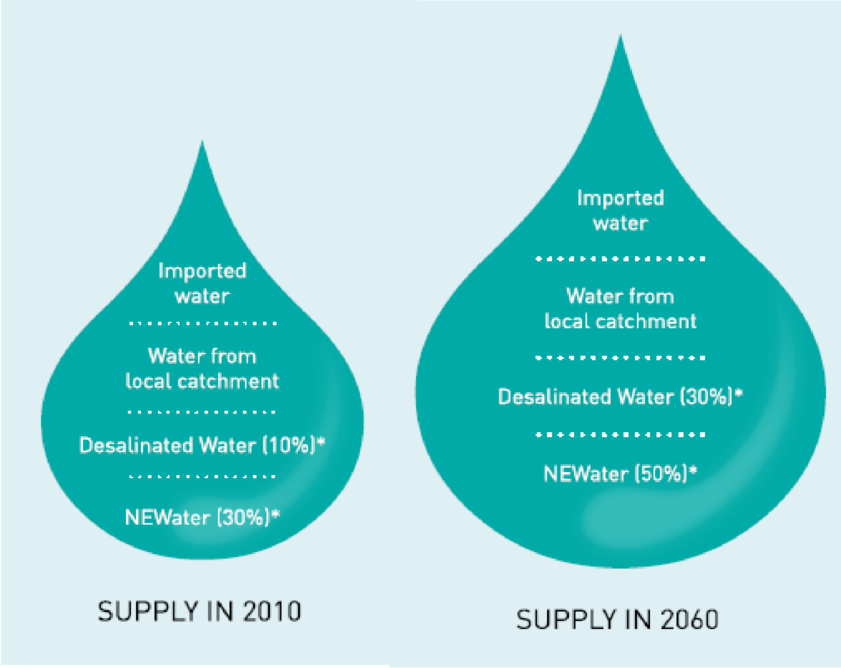
Desalination in Singapore

- Infinite resource
- Readily available
- Enable water self-sufficiency in Singapore

By 2060, desalinated water will contribute **30%** of Singapore's water demand, increase from 10% currently

BUT…

Energy consumption is high (about 3.5 kWh/m^3 with RO)



R&D Approach – Journey to Low Energy Seawater Desalination

Current 3.5 kWh/m^3

- Variable Salinity Process : 1.7 kWh/m^3
- Memstill (with waste heat): 1.0 kWh/m^3

Short-term < 1.5 kWh/m^3

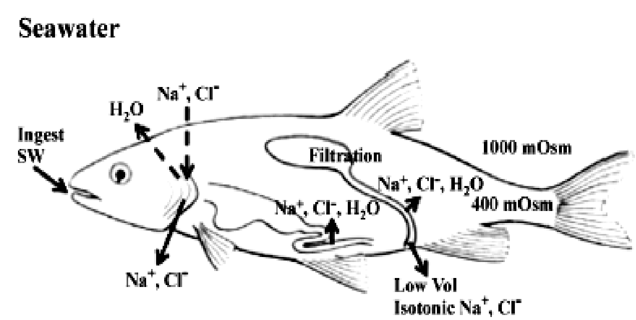
Breakthrough R&D

Long- term < 0.75 kWh/m^3

Biomimetic Membranes ; Biomimicry of Natural Desalination Processes

Aquaporins

Mangrove



Desalination – Current Status

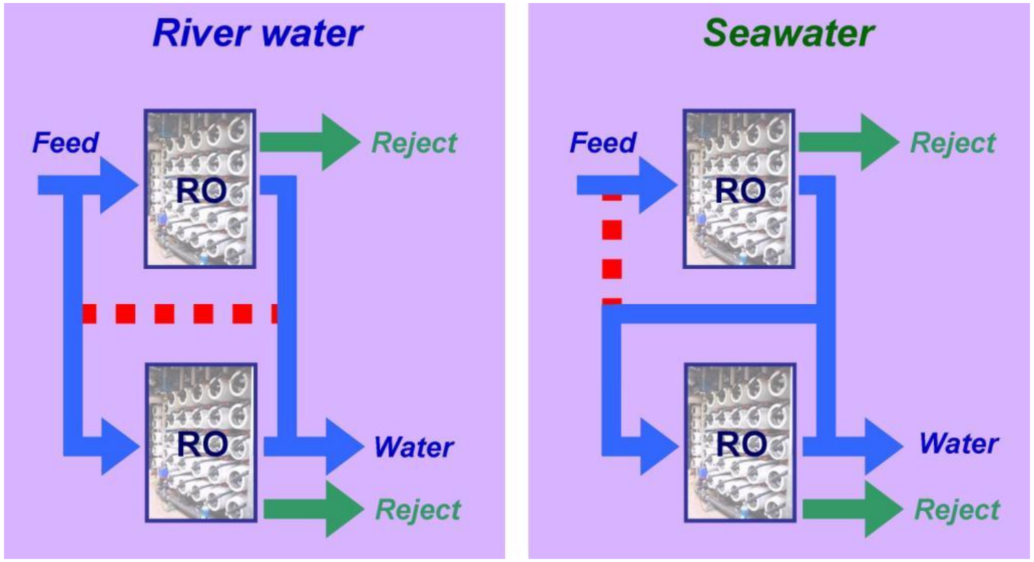
Membrane Distillation for Desalination

- Heat recovery process to produce distilled water for drinking / process water
- Uses low-grade waste heat from industries
  → Using waste heat as a resource
  → Potential to recover 40 – 160 MGD of water from JI industries
- Energy consumption < 1 kWh/m^3 obtained through pilot-scale studies
- Water quality is better than NEWater


Memstill® module

Variable Salinity Process

- To tap the small canals in the fringe catchment to augment Singapore's water supply
- Able to treat canal water and seawater interchangeably
- Developed from Pilot to Demo-scale in 2-3 years.
- VSP Demo plant completed in July 2007.
- Demo plant allowed for the testing of assumptions and predictions
- Achieved mode of operations: 60% freshwater and 40% seawater



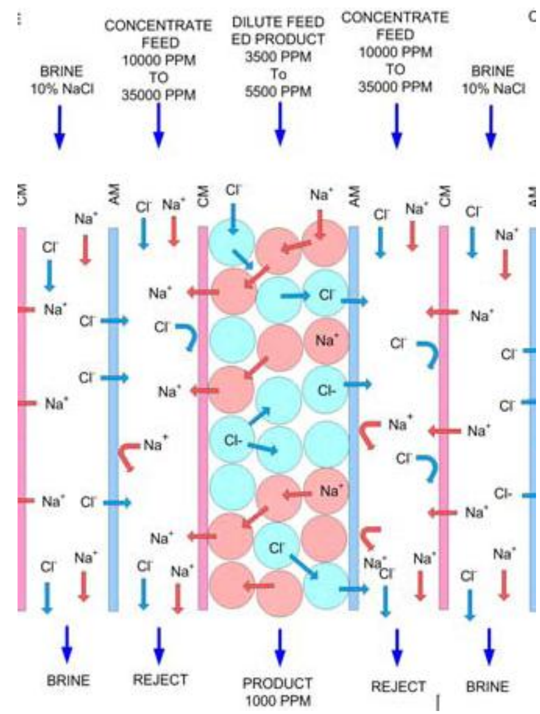
Benefits:

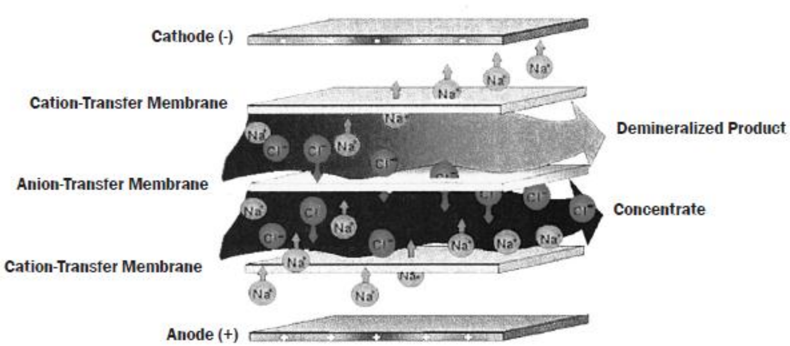
✓ Lower energy consumption: 3.5kWh/m^3 to 1.7kWh/m^3

✓ Increase catchment area from two-thirds to 90% of Singapore's land area

Novel Electrochemical Desalination Technology

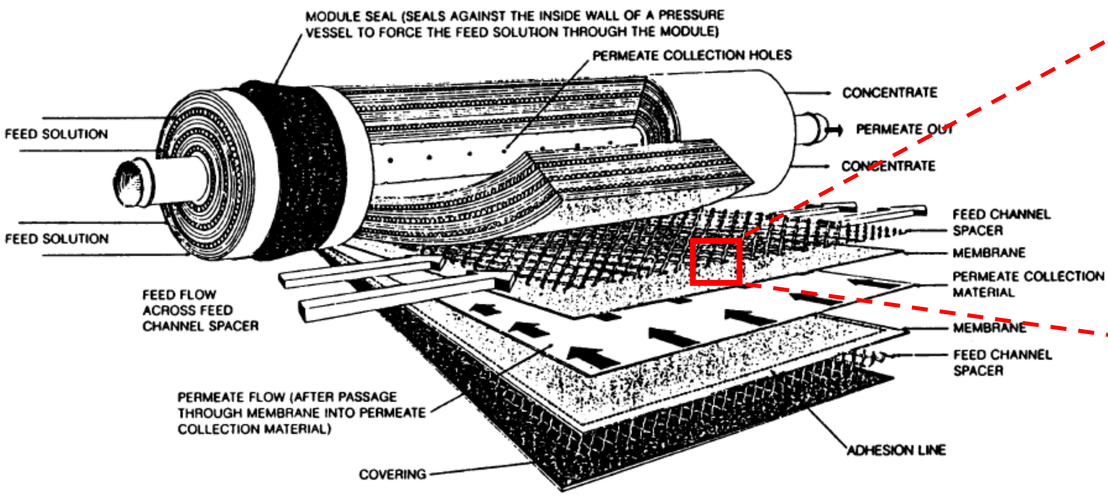
- Project awarded under EWI's challenge call in 2007 to reduce energy consumption for desalination to <1.5 kWh/m^3
- 50 m^3/day ED/CEDI system commissioned in Feb 2011 in VSP at Tampines
  - Energy consumption: 1.4 – 1.8 kWh/m^3
  - Recovery of 20 – 35%
  - Optimisation of operating conditions ongoing
- Commercial unit currently being designed
- Further demonstration studies to be carrie out in PUB's installations

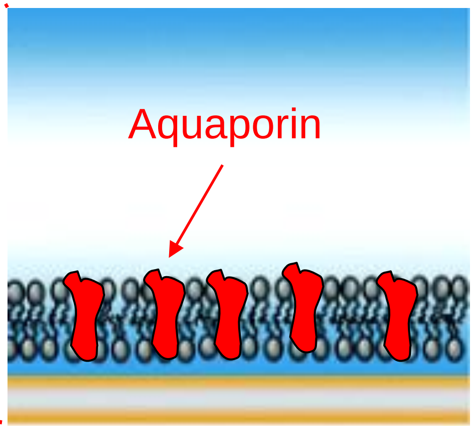




Desalination – Peek into the Future

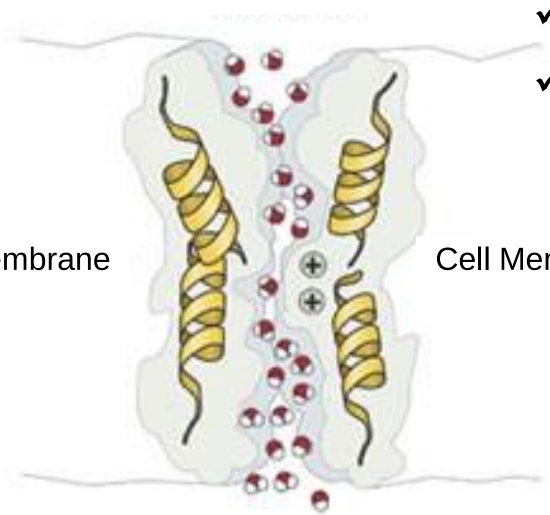
Biomimetic Membranes – Inspiration from Human Kidney





Aquaporin:

- ✓ High water flux
- ✓ Quantitative rejection of Na^+ and Cl^- ions



Potential Applications:

1. Seawater desalination membrane
   → 3.5kWh/m³ to 0.75kWh/m³
2. RO membrane for NEWater production
   → 0.8kWh/m³ to 0.3kWh/m³

Biomimicry of Natural Desalination Processes

High Salinity Water

Marine Algae

Marine Fish

Brackish Water Fish

Access to Ideas and Expertise through Partnerships

Local Academic Institutions

NUS National University of Singapore
Nanyang Technological University
Agency for Science, Technology and Research
Tropical Marine Science Institute
Ngee Ann Polytechnic
Singapore Polytechnic
NEWRI
iESE
SMTC
Stanford
NEMS
AEBC
DHI Water & Environment
R3C
Republic Polytechnic
NUS Environmental Research Institute
singapore-delft water alliance

Local Water Companies

Keppel Corporation
Hyflux™
salcon
sembcorp
United Engineers Limited
DAYEN
GrahamTek
optiqua
Ultra-Flo
MINT
美能 MEMSTAR
DARCO Solutions to Water & Waste

PUB
Water for All: Conserve, Value, Enjoy

Overseas Institutions

Global Water Research Coalition
MIT
ETH
Sandia National Laboratories
University of Canterbury
UNSW The University of New South Wales Sydney • Australia
University of Oxford
Illinois University of Illinois at Urbana-Champaign
Awwa Research Foundation Advancing the Science of Water
CSIRO
TU Delft Technische Universiteit Delft
kiwa
The University of Queensland Australia
Peking University 1898
wl | delft hydraulics
Flinders University
The University of Western Australia
Stanford University

Global Water Players & Utilities

SIEMENS
NITTO DENKO
Queensland Government
Black & Veatch
'TORAY'
suez environnement
GE
Veolia Environnement
Rand Water
Dow Living. Improved daily.
Norit
Teijin Human Chemistry, Human Solutions
AsahiKASEI
kuraray
Meiden
Mekorot Israel National Water Co.
Kurita
CDM
Orange County Water District Since 1933 A Tradition of Innovation
Metawater
Saline Water Conversion Corporation
CH2MHILL

Concluding Remarks

- Seawater desalination is critical for water sustainability in Singapore
- Continuous R&D is important to overcome water challenges through
  - ✓ Pilot-testing in PUB's installations
  - ✓ Demonstration testing for operational experience & validation testing
  - ✓ Collaborations with various partners
- Technologies developed locally can be adopted by water-stressed coastal countries

Thank You